INVESTIGATION OF ADAPTING NAVAL ARCHITECTURE AND MARINE ENGINEERING DESIGN PROCESSES TO DIGITAL COMPUTER SOLUTIONS

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Investigation of Adapting Naval Architecture and Marine Engineering Design Processes to Digital Computer Solution

by

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ABSTRACT

This thesis investigates the feasibility of adapting Naval Architecture and Marine Engineering design processes to digital computer solution.

Two problems, the determination of critical whirling frequencies of propeller shafts and the determination of stresses in a transverse web frame are programmed for a digital computer. A detailed explanation of the programs and a discussion of the methods of approach and difficulties encountered in adapting the solutions of these problems to a digital computer is included. The most important results obtained from programming

these problems are experience with and knowledge of digital computers. Applying this knowledge and experience to the general field of naval architecture the following conclusions and recommendations are presented:

Conclusions:

a. Digital computers are applicable to naval architecture problems.

b. The average naval architect has sufficient background to program a digital computer.

c. A programmer should have a complete engineering understanding of the problem and some familiarity with numerical methods of mathematical processes.

d. In general the limitations imposed by the computer on a problem are no more restrictive than those imposed by manual methods.

e. The digital computer used should be able to handle numbers usually encountered in engineering problems.

Recommendations:

a. Digital computer should be used in naval architecture.

b. Digital computers are suited for theses and research problems.

c. Any future thesis should only consider the computer as an aid in the solution of a specific problem and not general applicability of the computer.

d. For engineering applications the programmer should have; (a) a good engineering understanding of his field; (b) knowledge of numerical methods of mathematical processes; (c) organizational abilities.

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Introduction

The field of naval architecture contains some of the most complex problems facing the engineering profession in this modern day and age. A ship is a structure containing a network of mechanical equipage that is unequaled by any other movable structure in the world. The complexity of such a structure almost defies analytic approach and as a result much of the design work is based on previously built vessels. A parent design is altered by repeating various numerical procedures until the desired result is obtained. The practice of naval architecture can best be described as laborious and repetitive with a necessity for a background of experience.

In an effort to eliminate the necessity of utilizing personnel to perform laborious calculations, following World War II a committee was appointed by the Bureau of Ships to investigate and report on the applicability of utilizing machine aided calculations for problems arising in the preliminary design stage. Due to the stage of development of electronic computers at that time an analog computer was developed for stability calculations in the preliminary design. Although this investigation did consider the application of digital computers to problems in the preliminary design stage, the application to the general field of naval architecture was not fully considered. (11)[1]

The purpose of this thesis is to investigate the applicability of digital computers to the field of naval architecture, with primary emphasis on structural design problems, to acquaint the authors and other

1. Numbers in parentheses refer to the Bibliography at the end of the thesis.

naval architects with this new method of approach, to determine the type problems best suited for computer solution and publish some of the difficulties encountered, to determine the type of person required to utilize most effectively the machine aids and to incite interest in applying digital computers in the investigation of problems heretofore considered too laborious and time consuming to analyze by hand calculations. To do this the authors had to first acquaint themselves with an existing computer and secondly, to pick sample engineering problems of generic nature for specific programming.

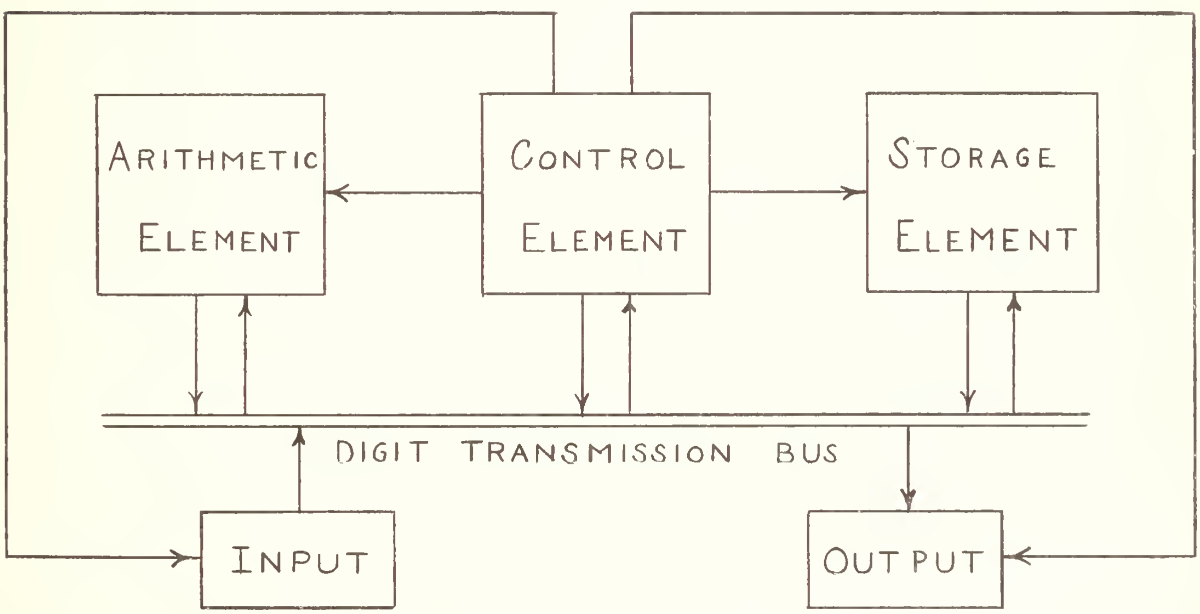
The authors are graduate students in naval architecture whose studies have been primarily channeled in the direction of hull structures. The background in mathematics included calculus through differential equations and a basic course in vector and complex mathematics. Their background in mathematics is no better than can be expected from the practicing naval architect.

Two problems were picked as samples, one, calculation of the whirling frequencies of a propeller shafting arrangement and two, an analysis of an indeterminate structure of five degrees of indeterminancy. These problems were picked because they are examples of types that require reiterative procedures in their solutions. Further, both problems had solutions that had been previously determined by hand.

The digital computer investigated and utilized was the Whirlwind I computer at MIT. This computer started operations in November 1950 and has been used as a guide for the development of many commercially available machines today. For this reason the general conclusions drawn from an analysis of the applicability of Whirlwind I should apply to any machine considered for particular problems, although other machines may have different capabilities.

Basically, all digital computers utilize the same theory of operation. They all contain the following elements: storage element, control element, arithmetic element and input and output devices, as depicted in Figure I.

Calculations are performed in the arithmetic element utilizing the numbers and instructions contained in the storage element. Input and output devices are used to get information in and out of the computer. The control element makes the components function.



Schematic Diagram of Digital Computer

Figure I

The discussion of the individual elements that follows pertains to Whirlwind I only, although other computers have similar equipment that performs the same functions.

The storage element consists of 2048 registers or "cells." Instructions or numbers are stored in these registers by impressing electrical pulses on magnetic cores. Each register contains 16 such cores and, therefore, the basic word-length is 16 digits. The pulses may be either positive or negative and the resulting direction of magnetization determines whether the digit represented is 0 or 1. This means that all the machine claculations are carried out in the binary number system. In every register the first binary digit represents the sign of the number and the remaining 15 binary digits can represent approximately 5 decimal digits.

Instructions are stored in the registers in a slightly different manner. Here the first five binary digits represent the mathematical operation that is to be performed when the instruction is obeyed. The remaining eleven binary digits represent the location of the register containing the number on which the operation is to be performed.

The permanent storage of Whirlwind I may be increased to approximately 22,000 registers by the use of a magnetic drum. This device is somewhat slower in the transfer of information than is the permanent storage, but it is very convenient for the solution of long problems.

The arithmetic element consists of three registers. In one of these, called the accumulator, or "AC" register, the basic arithmetic operations of addition and subtraction are performed. Multiplication and division are accomplished by a series of these two basic operations.

The input devices are a photoelectric tape reader and a mechanical tape reader. These devices read into the storage element coded information from a punched paper tape. They convert holes in the tape into electrical signals to properly magnetize the registers of the storage element. A conversion routine is available to transform decimal information on the tape into binary information for storage in the computer. This feature is a great aid in programming and enhances the flexibility of the computer.

The output devices available are flexowriters, five magnetic tape units and an oscilloscope and camera. The desired output information can be typed out directly by flexowriters, or it can be stored on magnetic tape and typed out by the flexowriter at a later time. The latter procedure saves computer time since it is much faster to read information onto magnetic tape than to type it. Another method of getting the information out is to display it on the oscilloscope and photograph it. This saves typing time, but the film must be processed. However, it is convenient for reproducing the results. Standard output programs are available or special ones may be written to get the information out in the form desired. For instance, numbers may be in octal or decimal system; written in columns, lines, blocks, or tabulated; formed raised to a fixed power of ten or with a fixed decimal point. This flexibility of output is an important feature of digital computers.

Control Element

Each of the various components of the computer consists of combinations of electrical circuitry and transfer buses. Only through intelligent control of these devices can electrical signals be made to

perform arithmetic operations. The control element performs this function by causing the flow of magnetic signals to reach the proper element at the appropriate time. Basically then, the control element is a switching device that channels the information through transfer buses to itself and the other elements. To do this, the control element must interpret the program instructions, which are themselves magnetic signals, into other magnetic signals which control the operation of the computer.

The speed of operation of the computer depends upon the memory access time and the time required to integrate a number of switching combinations into a useful operation. Switching is performed by utilizing electrical impulses from a high frequency oscillator. A new set of switching combinations can be established for each time pulse received by the control element. The time required to perform an operation depends on the number of impulses necessary to perform the switching and the repetition rate of the impulses. In Whirlwind I the pulse repetition rate is 1 micro-second. At this rate the addition of two numbers requires 48 micro-seconds and multiplication requires approximately 65 micro-seconds. Using the conventional rating system which is the number of additions a computer can perform per second, the Whirlwind I is rated at 20,000 operations per second.

The instructions necessary to perform the desired mathematical calculations are called a program and are fully explained in Appendix A. For each computer there exists a standard instruction code. By ingenious combinations of these standard instructions the programmer can cause a computer to perform the requisite numerical calculations.

One of the more important instructions is the "conditional response." This instruction allows the computer to make an either-or decision based on the sign of the number in the accumulator. As a result of this capability the computer can be made to cycle back through a series of instructions any desired number of times. The cycling ability is ideally suited to repetitive processes which are useful in design calculations.

Digital computers have been widely used in other fields of engineering and new adaptations are being developed every day. Some of the more important uses developed are:

(1) Aircraft weight, balance and thrust calculations.

(2) Steam turbine design

(3) Catapault launching analysis

(4) General structural application in the aircraft industry.

PROCEDURE

General

In order to accomplish the objectives discussed in the introduction it was necessary that some knowledge of computers be obtained. A twenty-five hour course in programming for Whirlwind I was completed by the authors to partially fulfill this requirement.

Once the capabilities of the computer were realized, it was necessary to decide what problem would best prove the basic contentions. Probably the biggest single factor in this decision was time. A very complicated problem would require a great deal of time to program while a simpler problem would not test the authors' ability.

A compromise was reached by deciding to program two problems. The first should be a relatively short and uncomplicated problem aimed at giving the authors' experience with the computer and also making some contribution to naval architecture. The second problem should be of such size and complexity that its solution would more fully describe the abilities of the computer and the benefits of computer applications to naval architecture.

The first problem programmed was the determination of the whirling frequencies of propeller shafts. The method of solution was developed by Professor F. M. Lewis. This problem was selected because the method of solution is an iteration process ideally suited to computer application. Furthermore, the problem was short and each step had been delineated by hand calculations performed by Professor Lewis. This last reason was very important because it enabled the authors to check their work and to ascertain the accuracy of the program.

The second problem programmed was the determination of stresses in a transverse web frame. A procedure similar to the one used in the Bureau of Ships was adapted to the computer. The numerous computations encountered in this problem made a computer solution very desirable. The calculations were made for a new destroyer type for which a partial check of the numerical results was available. Another important reason this problem was selected was to further the authors' knowledge in structural analysis of a ship. The course of instruction in naval architecture had not included the calculation of transverse strength.

PROPELLER SHAFT WHIRLING FREQUENCIES

Description of the Problem

Basically, the problem is to calculate the whirling or lateral frequency of a propeller shaft system in which the excitation is induced by the propeller. The method of calculation involves a numerical solution of a fourth degree differential equation of the form

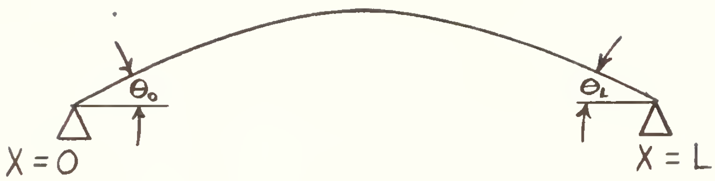
$$\frac{d^4y}{dx^4} - \frac{m\omega^2}{EI}y = 0$$

of which the general solution is of the form

$$y = C_1 \sin \lambda x + C_2 \cos \lambda x + C_3 \sinh \lambda x + C_4 \cosh \lambda x$$

where

$$\lambda^4 = \frac{m\omega^2}{EI} \qquad \lambda L = \beta$$



let $y' = \theta$ and $y'' = \Psi$. Applying boundary conditions to determine the constants of integration: at $x = 0$

$$C_2 = \frac{-\Psi}{2\lambda^2} \qquad C_4 = \frac{\Psi}{2\lambda^2}$$

$$C_3 = \frac{\frac{\Psi}{2\lambda^2}(\cos\beta - \cosh\beta) - \frac{\theta}{\lambda}\sin\beta}{\sinh\beta - \sin\beta}$$

$$C_1 = \frac{-\frac{\Psi}{2\lambda^2}(\cos\beta - \cosh\beta) + \frac{\theta}{\lambda}\sinh\beta}{\sinh\beta - \sin\beta}$$

at $x = L$

$$\theta_L = \frac{\Psi_0}{\lambda}\left(\frac{\cos\beta\cosh\beta - 1}{\sinh\beta - \sin\beta}\right) + \theta_0\frac{(\cos\beta\sinh\beta - \sin\beta\cosh\beta)}{\sinh\beta - \sin\beta}$$

$$\Psi_L = \frac{\Psi(\cos\beta\sinh\beta - \cosh\beta\sin\beta)}{\sinh\beta - \sin\beta} - \frac{2\theta\lambda\sin\beta\sinh\beta}{\sinh\beta - \sin\beta}$$

then writing

$$\theta_L = -(\theta_0 S_1 + \Psi_0 L S_2)$$

$$\Psi_L = -(S_1\Psi_0 + \theta_0/L\, S_3) = \frac{m_L}{EI}.$$

From which

$$S_1 = -\frac{\cos\beta\ \sinh\beta - \sin\beta\ \cosh\beta}{\sinh\beta - \sin\beta}$$

$$S_2 = -\frac{\cos\beta\ \cosh\beta - 1}{\beta(\sinh\beta - \sin\beta)}$$

$$S_3 = \frac{2\beta\ \sin\beta\ \sinh\beta}{\sinh\beta - \sin\beta}$$

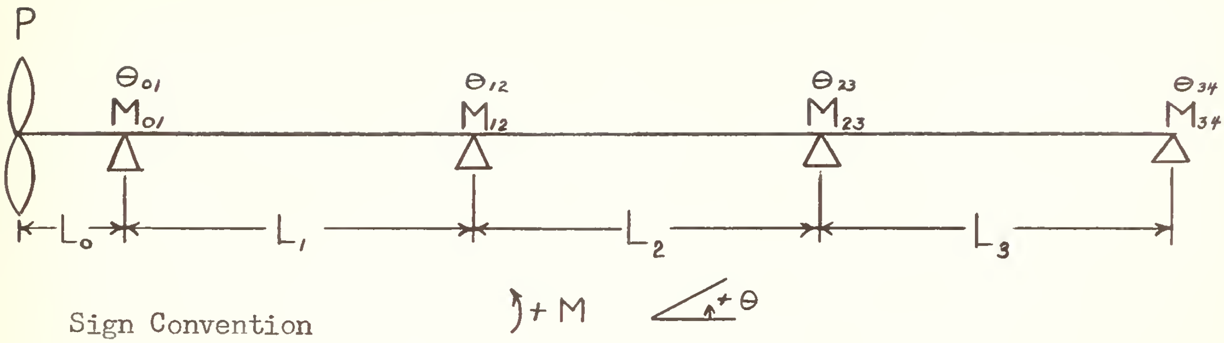
The above equations are applicable to one span of the shaft. In the solution of this problem these equations were used to determine the moment and angle of rotation at the end of one span and then carry these results over to the next span. The number of spans to be used is unspecified, however, it is the opinion of the authors that four spans give sufficient accuracy.

Since

$$\omega = \frac{\beta^2}{L^2}\sqrt{\frac{EI}{m}}$$

various values of β are assumed and the residual moment at the free end plotted versus the frequency. The value at which the end moment becomes zero is a resonant point or natural whirling frequency of the shafting system.

In applying these equations it is useful to determine certain parameters in terms of the physical properties of the shaft system. These are given below and the notation is explained in Figure I.



Schematic Diagram of Shaft

Figure I

It can be shown from the equations previously developed that

$$m_{01} = - \frac{E_0 I_0}{L_0} \left[\frac{\phi_W + \phi_J - \frac{\phi_W \phi_J}{3}}{1 - \frac{\phi_W}{3} - \phi_J + \frac{\phi_W \phi_J}{12}} \right]$$

where

$$\phi_W = \frac{W_p L_0^3 E_1 I_1}{W_1 L_1^3 E_0 I_0} \pi^4 \left(\frac{\beta}{180}\right)^4$$

$$\phi_J = \frac{J L_0 E_1 I_1 \left(\frac{1}{2} \mp \frac{1}{q}\right)}{W_1 L_1^3 E_0 I_0} \pi^4 \left(\frac{\beta}{180}\right)^4$$

and

J = polar moment of inertia of propeller and entrained water.

q = the order of vibration being investigated.

The number subscripts refer to spans as shown in Figure I.

From the above it can be seen that

$$m_{12} = -(s_{11}m_{01} + c_{a1}s_{31})$$

$$\theta_{12} = -(s_{11}\theta_{01} + m_{01}s_{21}/c_{a1})$$

where

$$c_{a1} = E_1I_1/L_1$$

Here the second number subscripts refer to the span. It should be noted that θ_{01} is assumed as unity.

For determining s_1, s_2, s_3 for different spans it is convenient to use the following:

$$\beta_2 = \beta_1 \sqrt[4]{\frac{c_{d1}}{c_{d2}}}$$

where

$$c_{d1} = \frac{E_1I_1}{W_1L_1^3}.$$

The procedure described is repeated for each end moment and angle of rotation until the residual end moment, m_{34} is determined. Then a new value of β_1 is assumed and the process repeated until a series of end moments versus frequencies results are generated. By plotting these values, or by interpolation, the critical whirling frequency can be found.

General Discussion of Program

The method developed for solution of the propeller shaft whirling frequencies is ideally suited to computer solution because it is essentially one of numerical iteration. Various values of β_1 are assumed and the residual moment calculated for any number of spans. Since the labor involved in programming is the same regardless of the number of times a process is repeated, good accuracy can be obtained with no extra effort by the programmer and small increase in cost of operation of the computer.

The underlying guide in programming this problem was to make it as general as possible. This was done so that anyone wishing to use this method in the future would merely have to change a few numbers to adapt this solution to his particular problem. The quantities to be changed were grouped separately at the beginning of the program and involve such factors as the physical characteristics of the propeller and shafting, the number of spans to be considered and the order of the vibration being investigated.

The first step in programming was to assign floating addresses or "flads" to registers which were to hold the numerical quantities and key instructions. These flads contain the numbers or instructions upon which mathematical operations are to be performed. The purpose of floating addresses is to simplify programming by enabling the programmer to refer to a flad rather than an absolute address each time an instruction is written. The advantage of this system is clearly demonstrated in the programs contained in the appendix. The flads used in programming and the numbers they represent are given in Appendix B.

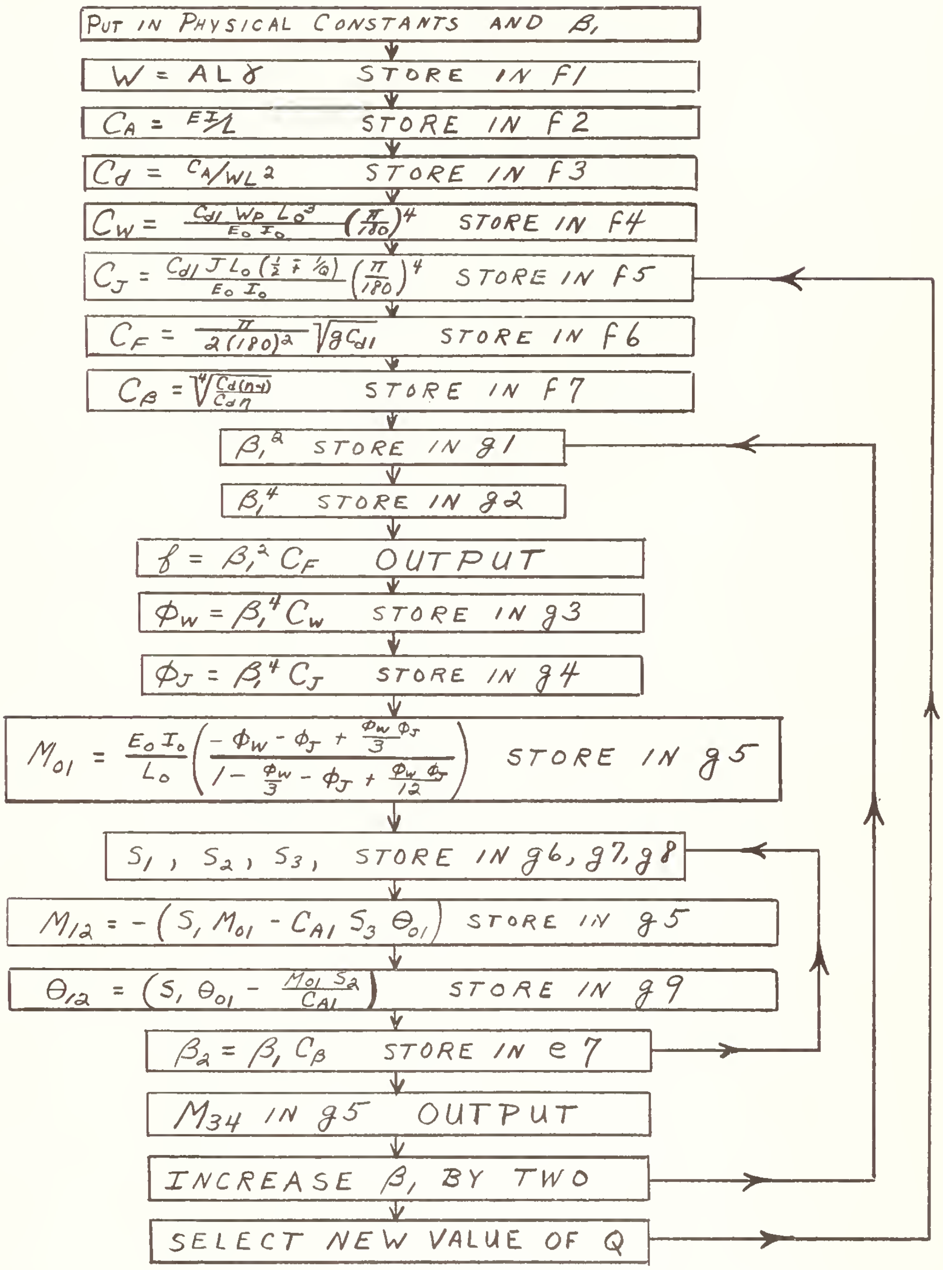
In addition to storing the data and constants of any problem, registers must be assigned to store intermediate results and for temporary storage.

The addresses of key instructions were assigned flads to aid in writing the program. For example, the flad, hl is the address of the first instruction in the program. After all the information has been fed into the computer the following instruction is used, "START AT hl" and the program begins.

After the flad assignments had been made, the next step was to draw a flow diagram such as shown in Figure III. The purpose of this diagram was to aid in the organization of the program and to provide an orderly procedure for the programmer to follow. It was a picture of the problem showing the sequence of operations to be performed. The programmer then wrote a short routine that would do the calculations of each section shown in the flow chart. The last step, then, was to combine these separate routines into one program that would solve the entire problem. Of course considerable care must be exercised in writing and combining these routines since the results of one section will influence the calculations in the following sections.

When the values of frequency and residual end moment had been generated in the arithmetic element, they were transferred to a magnetic tape via an output procedure. When the program had been completed these results were then transferred to a flexowriter and typed. The results were presented in two columns of frequency vs. end moment. Thus, it was possible to determine the frequency at which the moment becomes zero by either linear interpolation or a plot of the data.

FIGURE III FLOW CHART



STRESS CALCULATIONS FOR A NON-SYMMETRICALLY LOADED WEB FRAME

Description of the Problem

A transverse web frame is a part of a system of frames and bulkheads that maintains the shape of the hull. A sketch of a web frame is given in Figure IVa. To do this it must provide support for longitudinal strength members and carry vertical shear loads from the decks and hull bottom into the sides which are the main vertical shear carrying members of the structure. The web frame is a continuous beam ring that encircles the hull girth in a transverse plane. All loads applied to the frame are assumed to lie within this plane, but may have any orientation within that plane. Under such loading a web frame must resist axial loads, shear loads and bending loads. Since web frames are generally very long with respect to depth, bending moments are by far the most important aspect to be considered in the solution.

Due to the complex interaction between the webs, longitudinals, and bulkheads, the exact solution of the problem of web frames and the system of members that maintain the hull shape has defied rational engineering theory up to this time. Time limitations and the intent of this thesis prohibited an investigation of possible improvements in the method of the transverse strength calculations. It was decided to adapt to a computer solution a proven method. Although transverse strength calculations are not always performed for modern ships, the analysis normally utilized, if performed, is a long, laborious method developed by J. Bruhn[2][6].

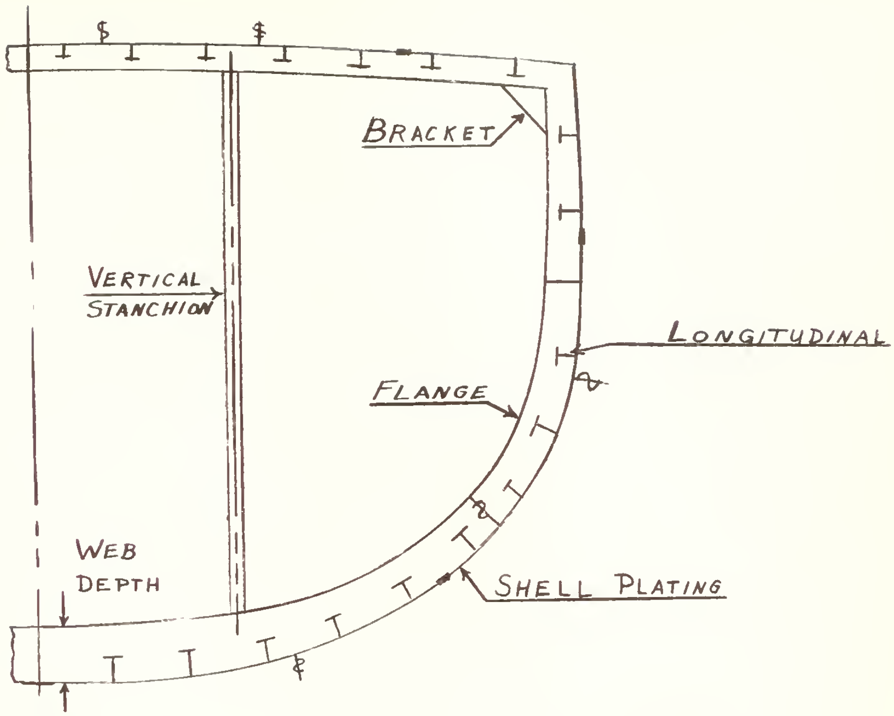


Figure IVa Transverse Web Frame, Starboard Side

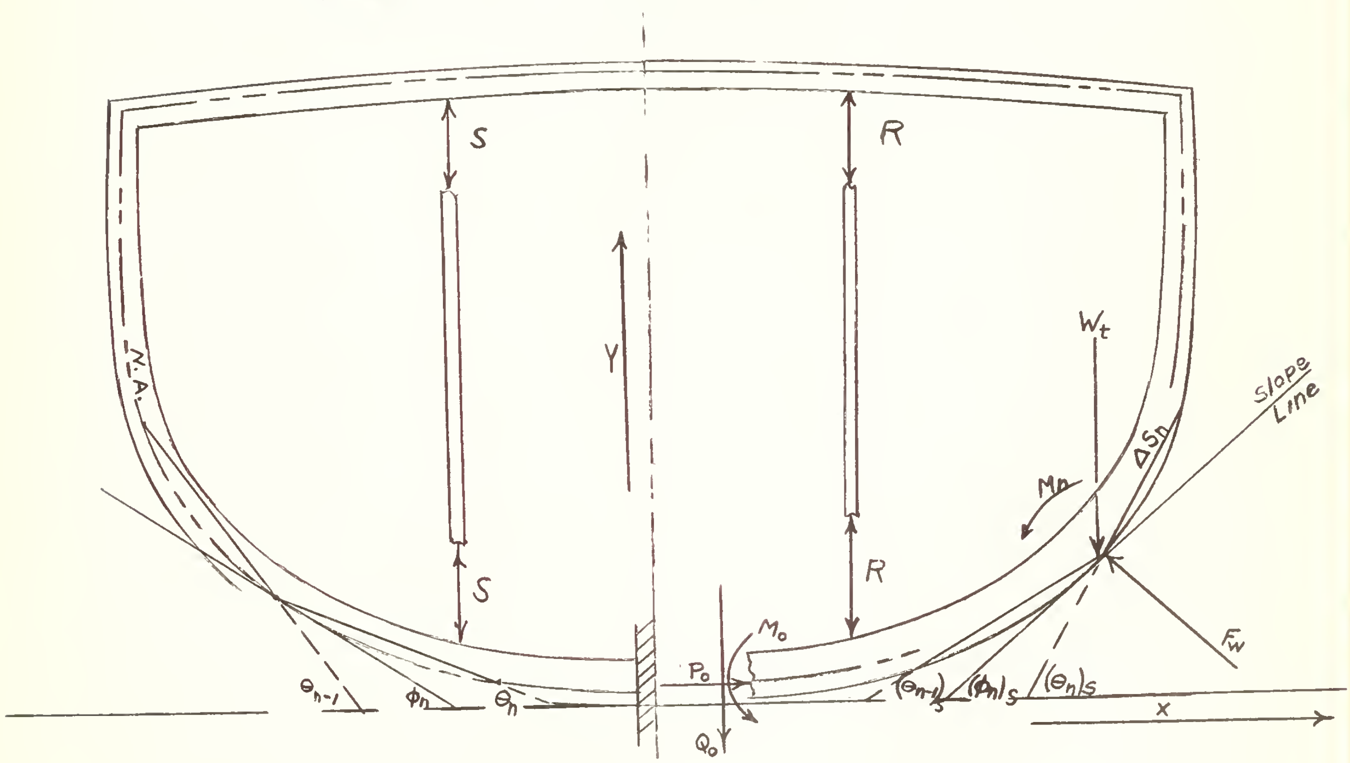


Figure IVb Web Frame Showing Redundant Forces

Bruhn's method is an adaptation of Castigliano's theorem of least work which states that "The redundant reaction components of a statically indeterminant structure are such as to make the internal work a minimum."[10] Determination of each of the redundant components requires that the differential of the total internal energy with respect to that redundant be equal to zero which is a minimum energy condition. Bruhn neglected the axial and shear components of energy and considered only the larger bending effects. Bruhn's basic energy equations for a web frame with two stanchions, as shown in Figure IVb, then become

$$U = \frac{1}{2E}\int \frac{m^2}{I}\, ds$$

where $m = m_0 + p_0\, y + q_0\, x - m_v - m_H + R(x-x_a) + S(x-x_b)$

$$\frac{\partial u}{\partial p_0} = \frac{1}{2E}\int_0^{0'} \frac{2m}{I} \cdot \frac{\partial m}{\partial p_0}\, ds = 0$$

$$\frac{\partial u}{\partial q_0} = \frac{1}{2E}\int_0^{0'} \frac{2m}{I} \cdot \frac{\partial m}{\partial q_0} \cdot ds = 0$$

$$\frac{\partial u}{\partial m_0} = \frac{1}{2E}\int_0^{0'} \frac{2m}{I} \cdot \frac{\partial m}{\partial m_0}\, ds = 0$$

$$\frac{\partial u}{\partial R} = \frac{1}{2E}\int_{B_1}^{B_2} \frac{2m}{I} \cdot \frac{\partial m}{\partial R} \cdot ds = 0$$

$$\frac{\partial u}{\partial S} = \frac{1}{2E}\int_{B_3}^{B_4} \frac{2m}{I} \cdot \frac{\partial m}{\partial S}\, ds = 0$$

$$\frac{\partial m}{\partial p_0} = y$$

$$\frac{\partial m}{\partial q_0} = +x$$

$$\frac{\partial m}{\partial m_0} = 1$$

$$\frac{\partial m}{\partial R} = (x-x_a)$$

$$\frac{\partial m}{\partial S} = (x-x_b)$$

Bruhn's working equations become:

$$\frac{1}{E}\int_{0}^{0'} y\,\frac{m}{I}\,ds = 0$$

$$\frac{1}{E}\int_{0}^{0'} x\,\frac{m}{I}\,ds = 0$$

$$\frac{1}{E}\int_{0}^{0'} \frac{m}{I}\,ds = 0$$

$$\frac{1}{E}\int_{B_1}^{B_2} (x-x_a)\,\frac{m}{I}\,ds = 0$$

$$\frac{1}{E}\int_{B_3}^{B_4} (x-x_b)\,\frac{m}{I}\,ds = 0.$$

Castigliano's first theorem states that, "the deflection in a certain direction at a certain point of a statically determinate structure is equal to the partial derivative of the total external work or the total internal energy with respect to a load applied at this point in the direction of the deflection."[10] Conversion of a statically indeterminate structure into a statically determinate structure by means of cutting the structure and applying redundant forces as loads allows the application of Castigliano's first theorem. The above equations then represent the deflection between the limits of the integration. Since the web frame is continuous, the deflections and rotations at the point of action of the redundants m_0, p_0 and q_0 are equal to zero. For the redundant column forces R and S, the columns are considered imcompressible and the vertical deflection between the column ends is equal to zero. This idea of deflections and rotations is used in the description and analysis of the problem in Appendix B.

To determine the redundants, five simultaneous equations must be formed and solved. In a problem that contains more or fewer redundant supports such as stanchions or decks, the number of redundant equations required to solve the web frame would of necessity be changed to form one equation for each redundant force.

After the equations had been developed and formed into a matrix, Crout's method of matrix reductionwas used to solve for the value of the redundants. These redundants were then combined with the applied loads and the moments recomputed. Utilizing the computed moments, the stresses due to bending were calculated. The direct forces were converted into axial

and shear stresses. These stresses and the bending stresses were then added algebraically to give the total stresses in the flange of the web frame and shell of the ship.

General Discussion of Program

The flow diagram contained in Figure V describes the sequence of calculations used in calculating the frame stresses. A detailed description of the instructions utilized in each sub-routine and the sequence control program are contained in Appendix B.

Due to the normal manner of construction of ships, the web frames are constructed as a symmetrical ring frame of variable cross-sections. The loads, however, are very complex and for a general solution must be considered as non-symmetrical. Note that for this problem only the simple static loads are considered.

The contours of the ship's hull must be represented within the computer and, in order to find the neutral axis and to form the components of the loads, the slope of the contour must be computed at each station. The most obvious solution for the novice programmer is to form the equation of the contour and differentiate that equation to determine the slope. As novices this solution was attempted, but was soon abandoned due to the complexity of the program necessary to form the equation and the inherent error involved in first using approximate methods to form the equation and more approximate methods required to utilize the equation. The method finally selected was to choose a series of stations around the girth of the web and assume the web is represented by a series of short straight

Read in Crout's method sub-routine on drum other instructions and data to core memory

Form sin θ, cos θ, Δs of shell

Form components of water pressure loads

Form total vertical forces

Form sin ϕ, cos ϕ, of shell

Form $1/I$, A_t, $d_{N.A.}$, of frame

Block out all input data, and quantities formed except $1/I$ and A_t

Form coordinates of N.A.

Form sin ϕ and cos ϕ of N.A.

Form moments due to external loads

Form matrix of integrals

Block in Crout's method sub-routine

Solve matrix for the five redundants

Alter loads to include redundants

Form bending moments I

Block in d_w, t_s, t_f, $d_{N.A.}$

Calculate stresses σ_a, σ_b, σ_f, σ_s

Stop. Get output of σ_a, σ_b, σ_f, σ_s or from built in routine (fp tape)

Perform comparison and alteration routine

Figure Va Sequence of Operations for Web Frame Program

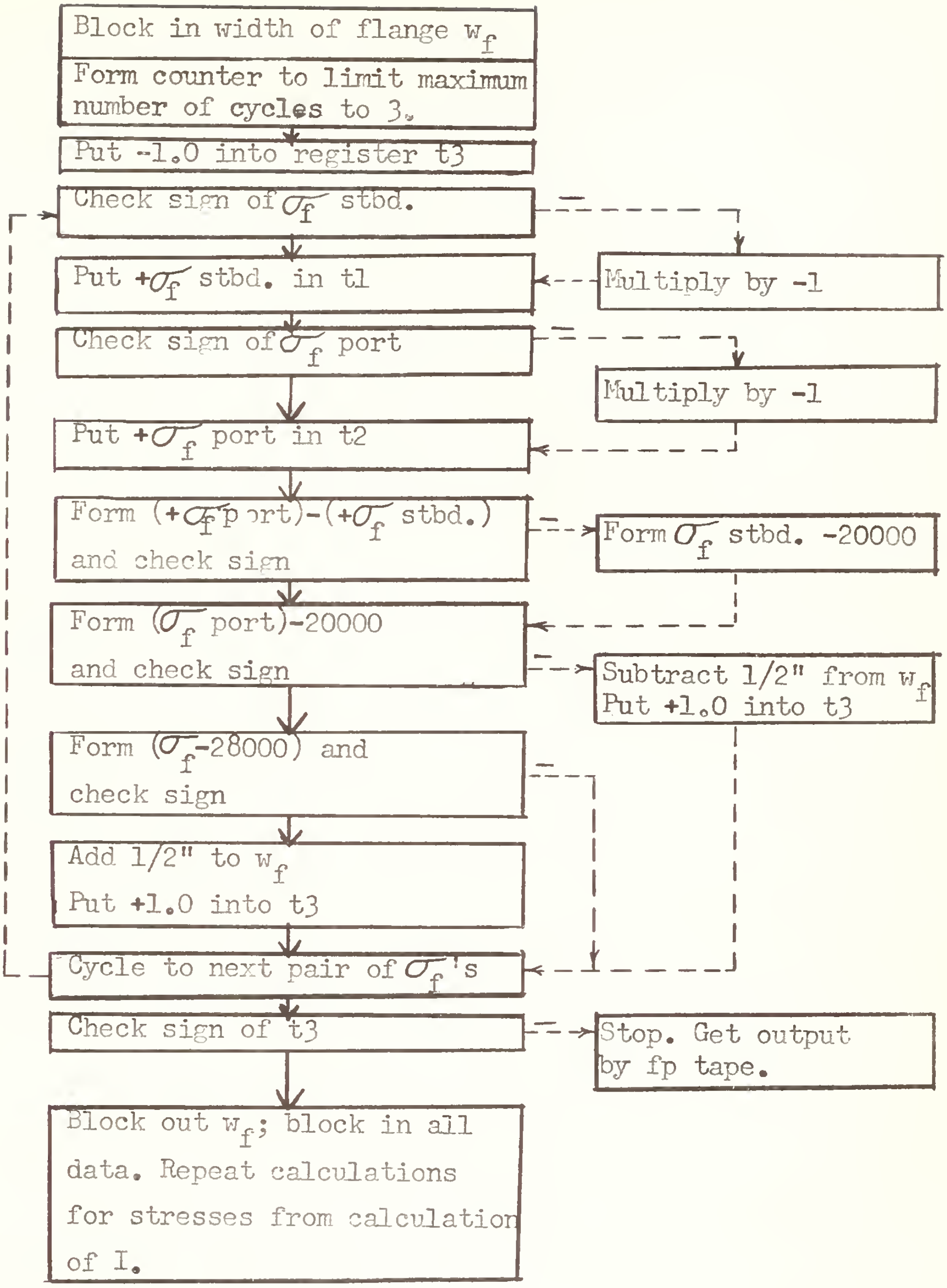


Figure Vb Comparison and Alteration Routine

beam segments. Stations were selected in such a manner that the angle change between segments was both small and nearly equal which, due to the variable curvature, makes each segment unequal in length. A station was necessary at the point of action of each redundant. Such a procedure follows a common philosophy of digital computers in that where complexity must be weighed against a greater number of calculations and simplicity, the choice must be made in favor of simplicity. The number of stations required to properly approximate the DD hull was 49 which should be sufficient to approximate the frame of any vessel.

Sin θ and cos θ were determined directly from the coordinates by using the Pythagorean Theorem and basic trigonometric relationships.

$$\Delta s = \sqrt{dx^2 + dy^2} \quad \sin\theta = \frac{\Delta y}{\Delta s} \quad \cos\theta = \frac{\Delta x}{\Delta s}.$$

This was done for two reasons, first, only the sin and cos are used in the solution and secondly, the $\tan\theta = \frac{\Delta y}{\Delta x}$ becomes infinity when $\Delta x = 0$ which is the case on ships with wall sides or tumble home. The computer will not handle division by zero and the operations will be stopped when such a case occurs. To approximate the functions of the tangent angle at each station, the functions of the chord angles were averaged. While $\sin\theta_1 + \sin\theta_2/2$ does not equal $\sin(\theta_1 + \theta_2)/2$, the error will be small as long as the change in θ is small which is another example of using a simple idea many times to obtain accuracy and generality.

Using the total water head which in the present problem was the height of the main deck and the average of the y coordinates of the

ends of the segments, the water pressure loads were determined and vertical and horizontal load components formed.

$$p_w = H - \frac{(y_1+y_2)}{2}$$

$$f_w = p_w ds$$

$$V_w = f_w \sin \theta$$

$$H_w = f_w \cos \theta.$$

Using the inputs of the web dimensions, the distance of the neutral axis ($d_{N.A.}$) from the hull shell was calculated and the moment of inertia about the neutral axis determined ($I_{N.A.}$)

$$d_{N.A.} = \frac{m_t}{A_t}$$

$$I_{N.A.} = I_{shell} - A_t d_{N.A.}$$

Knowing $d_{N.A.}$ and the ($\sin \phi$) and ($\cos \phi$) the offsets of the neutral axis from the shell could be determined.

$$x_{N.A.} = x_s - d_{N.A.}(\sin \phi)$$

$$y_{N.A.} = y_s - d_{N.A.}(\cos \phi).$$

Using the same procedure developed for the shell, the segment lengths and functions of the angle were formed.

One difficult engineering decision was the consideration of the sharp corner at the junction of the side shell and the deck edge. In normal practice the corner is bracketed and represents a point of complex discontinuity which nearly defies analytical analysis. After a number of methods were considered, it was decided to make the corner a "hard spot" by including the full bracket depth. The station spacing near the corner was reduced to minimize the effect of the corner. In all cases the tangent at the corner was taken as -1 which is equivalent to a slope angle of 135 degrees on the starboard side. This was done to form a smooth transition of the neutral axis around the corner.

The moment due to applied loads and water loads was determined by $m_n = H\,dy + Vdx$. The moments due to the redundant forces were: $p_0 y + q_0 x + R(x-x_a) + S(x-x_b)$.

The integrals of the moments were formed by the trapezoidal rule. While the trapezoidal rule implies linear segments between moment ordinates, this method was necessary to accomodate the random station spacing. The error resulting from the trapezoidal rule will be small as long as the station spacing is close and the moment curve is smooth. Both conditions are present in this problem.

After solving for the redundants and recomputing the moments and axial loads to include all forces, the direct stresses and bending stresses were combined. The program as written gives the alternative of performing a check calculation on the set of frame scantlings or of altering the frame scantlings to approach a more efficient design. The stresses were compared with allowable stresses and the section altered by changing the web flange

	M_o	P_o	Q_o	R	S	M_n
$\int \frac{M}{I} dS = \Delta\theta$	dI $2\int_0^A \frac{dS_n}{I_n}$	$dI+10$ $2\int_0^A \frac{Y_n}{I_n} dS_n$	$dI+20$ $\int_0^{0'} \frac{X_n}{I_n} dS_n = 0$	$dI+30$ $\int_0^{0'} \frac{(X_n - X_a)}{I_n} dS$	$dI+40$ $\int_0^{0'} \frac{(X_n - X_b)}{I_n} dS$	$dI+50$ $\int_0^{0'} \frac{M_n}{I_n} dS$
$\int Y \frac{M}{I} dS = \Delta x$	$dI+2$ $2\int_0^A \frac{Y_n}{I_n} dS_n$	$dI+12$ $2\int_0^A \frac{Y_n^2}{I_n} dS_n$	$dI+22$ $\int_0^{0'} \frac{X_n Y_n}{I_n} dS = 0$	$dI+32$ $\int_0^{0'} \frac{Y_n (X_n - X_a)}{I_n} dS$	$dI+42$ $\int_0^{0'} \frac{Y_n (X_n - X_b)}{I_n} dS$	$dI+52$ $\int_0^{0'} \frac{Y_n M_n}{I_n} dS$
$\int X \frac{M}{I} dS = \Delta Y$	$dI+4$ $\int_0^{0'} \frac{X}{I} dS = 0$	$dI+14$ $\int_0^{0'} \frac{XY}{I} dS = 0$	$dI+24$ $2\int_0^A \frac{X_n^2}{I_n} dS_n$	$dI+34$ $\int_{B_1}^{B_2} \frac{X_n (X_n - X_a)}{I_n} dS$	$dI+44$ $\int_{B_3}^{B_4} \frac{X_n (X_n - X_b)}{I_n} dS$	$dI+54$ $\int_0^{0'} \frac{X_n M_n}{I_n} dS$
$\int_{B_1}^{B_2} (x - x_a) \frac{M}{I} dS = \Delta Y$	$dI+6$ $\int_{B_1}^{B_2} \frac{(X_n - X_a)}{I_n} dS_n$	$dI+16$ $\int_{B_1}^{B_2} \frac{Y_n (X_n - X_a)}{I_n} dS$	$dI+26$ $\int_{B_1}^{B_2} \frac{X_n (X_n - X_a)}{I_n} dS$	$dI+36$ $\int_{B_1}^{B_2} \frac{(X_n - X_a)^2}{I_n} dS$	$dI+46$ 0	$dI+56$ $\int_{B_1}^{B_2} \frac{(X_n - X_a)}{I_n} M_n dS$
$\int_{B_3}^{B_4} (x - x_b) \frac{M}{I} dS = \Delta Y$	$dI+8$ $\int_{B_3}^{B_4} \frac{(X_n - X_b)}{I_n} dS_n$	$dI+18$ $\int_{B_3}^{B_4} \frac{Y_n (X_n - X_b)}{I} dS_n$	$dI+28$ $\int_{B_3}^{B_4} \frac{X_n (X_n - X_b)}{I_n} dS$	$dI+38$ 0	$dI+48$ $\int_{B_3}^{B_4} \frac{(X_n - X_b)^2}{I_n} dS$	$dI+58$ $\int_{B_3}^{B_4} \frac{(X_n - X_b)}{I_n} M_n dS$

Figure VI Arrangement of Matrix Formed by the Integration Sub-routine

width by predetermined incremental amounts. If $(\sigma_{allow} - \sigma_f) > 0$, then the flange was reduced. If $(\sigma_{allow} - \sigma_f) < 0$ then the flange was increased.

The outputs of each cycle change may be any computed value the programmer desires, but in the present problem the outputs were flange width, stress at the flange and at the shell, direct stress and shear stress at each point. Other methods of scantling change could have been utilized or the scantlings could have been altered by a complete change of scantlings around the girth. In the latter case each cycle would have required a decision by the programmer, a procedure that has considerable merit where design experience in the mind of the programmer can be better utilized. In the present problem it was decided to use the conditional response as another example of the digital computer's capabilities.

In the web frame problem the quantity of generated numbers necessary to produce a solution was so large that the auxiliary drum storage had to be utilized. Blocks of numbers were moved from the core memory onto the auxiliary drum to make room for calculations. Further, the size of the program was so large that optimum data output procedures could not be utilized without unwarranted complication of the program. The output data could have been typed or presented on films in columns of easily discernable numbers. In the present case the size of the program required output via an "fp" tape which gives five columns of numbers running consecutively across the lines and the address of the registers containing the numbers listed in the first column. Judiciously placed zeros provide separation between numbers of different meaning.

To make the program as general as possible sub-routines were utilized to perform the calculations. A full description of the use of a sub-routine is contained in Appendix A. The sub-routines used will perform the calculation of stresses for a web frame of any dimension and shape desired. However, the number of redundants of the frame cannot exceed five and the water pressure head must equal the height of the deck edge. Due to limitations of storage space, the sequence instructions used will permit the use of only 49 stations around the girth. All of the above limitations can be exceeded by minor changes in the program should the necessity arise.

RESULTS

The numerical results obtained from the computer solution of problem one are contained in Table I. Numerical results were not obtained for problem two.

More important than the numerical results are the programs themselves. Problem one has been run and is known to be correct. The sub-routines of problem two, with the exception of the sub-routine for forming the stresses, were run and found to check. When all of the sub-routines were run in conjunction with the sequence control program, several minor programming errors were found.

The first program will determine the critical whirling frequency of any propeller shaft where no more than four spans need be considered. It can be adapted to another shaft merely by changing the physical constants of the shaft involved.

The second program will, if the above mentioned errors are removed, determine bending, axial and shear stresses in a transverse web frame and, if desired, will adjust the size of the web frame until the computed stresses approach the allowable stresses. The program is general within the limitations stated below; the required inputs being the dimensions of the web frame, the location of the stanchions and coordinates or points on the transverse section, the weight and shear loads at these points and the hydrostatic design head above the keel. The following are the limitations of the program:

(1) the frame scantlings are symmetrical about the ship centerline;

(2) the points defining the transverse section must be symmetrical about the ship centerline and only 25 may be taken on one side;

(3) one of these points must be on the centerline keel, one on the deck centerline and one at each end of all the stanchions;

(4) the hydrostatic pressure head must be equal to or greater than the height of the deck edge and hydrostatic pressure loads are not generated for the deck;

(5) ship must be in upright position;

(6) only one centerline or two off-center vertical stanchions may be used.

Computer time for calculation of problem one was 10 minutes, but the typing time of the results was 20 minutes. Computer time for the solution of problem two was 10 minutes.

Frequencies from hand calculations		Frequencies from computer solutions
	+6 ORDER	
3.69 cps		3.870 cps
5.41		5.656
8.20		8.527
11.49		11.762
15. 00		15. 239
21.00		20.915
	-6 ORDER	
		3.870
		5.656
		8.527
Not Available		11.762
		15.239
		20.915
	+1 ORDER	
		3.870
		5.656
		8.527
Not Available		11.762
		15.239
		20.915

Critical Whirling Frequencies for Propeller Shaft

Table I

During the period that the thesis was being printed, the programming errors in the second program were remedied and the results listed in Table II were obtained. Table II contains the values of the redundants and the stresses at the keel and the deck at centerline. Due to the difference in station spacing between hand and machine calculations, the centerline points are the only coincident stations for the two methods of calculation.

		Hand Method	Computer Method
m_0		+72,144 -ft.	+46,395 -ft.
p_0		+20,841	+19,805
q_0		(assumed zero)	+282
R		+1925	+662
S		(assumed equal to R)	+662
$\sigma_a = p/A$	keel	-3880 #/sq.in.	-5193 #/sq.in.
σ_{flange}	keel	+30,750 #/sq.in.	+18,970 #/sq.in.
σ_{shell}	keel	-15,440 #/sq.in	-16,586 #/sq.in.
σ_a	deck centerline	+470 #/sq.in.	-1,000 #/sq.in.
σ_f	deck centerline	-10,480 #/sq.in.	+25,000 #/sq.in
σ_s	deck centerline	+3,350 #/sq.in.	-12,868 #/sq.in.

Results of Web Frame Stress Calculations

Table II

As shown in Table II there is little correlation between hand and machine calculated values. However, this lack of comparison is caused by two conditions. The most important condition is that the hand calculations have been found to be of doubtful validity. Several hand calculation errors were found and the scantlings used are not defined. Recent information indicates that the scantling values used in the Bureau of Ships hand calculations do not correspond with the scantling values presented in the contract plans used as a basis for machine calculations.

The other condition that causes a small error is the fact that summation of vertical forces does not equal zero. The difference between weight forces and buoyant forces must be balanced by vertical shear forces applied along the vertical sides of the hull. This shear force was taken from the hand calculations and was included in the input values for the program. The machine computed buoyant forces were different from hand computed values due largely to the difference in station spacing and the method of averaging the water pressure. Therefore, the input values of shear did not balance vertical forces computed by the machine. It is now obvious that the shear force values must be computed by a sub-routine in the computer program.

This lack of the means of proper comparison points out one other general rule of programming. The programmer should perform hand calculations for the problem being programmed using the method adapted to the computer. The authors decided that the use of existing hand

computations would be a time saving device; however, as the results indicate, this was a poor decision and it is hoped that future programmers will benefit by the author's experience.

With the exception of the shear error discussed above, the program does work and produces good results. With slight correction the web frame program is suited for research and engineering calculations.

The time required for machine calculations was 25 seconds; however, program conversion required five minutes and typing time for results of calculations required twenty minutes.

Time limitations did not permit the running of the comparison and alteration program for the web frame.

DISCUSSION OF RESULTS

The subject of computer application to naval architectural problems is as general as the field of naval architecture itself. Each proposed application will require a separate analysis of feasibility. However, certain general conclusions and impressions can be gained from the two problem examples of this thesis. To each general conclusion there exists certain possible exceptions; however, these exceptions only tend to prove the contention that digital computers are not universal panaceas, but only local aids.

The programming errors found in problem two are normal errors that occur in every program and do not reflect upon the method of approach. The nature of these errors are incorrect addresses, typographical mistakes and human errors. The correction of these difficulties is only a matter of time and patience.

The results of the two programs indicate that digital computers are applicable to long and complicated naval architecture problems and that the numerical results are more than comparable with those of hand calculations. Of greater engineering importance than accuracy, was the great reduction in calculation time obtained by computer usage. For the first problem the computer required 10 minutes as opposed to an estimated hand calculation time of thirty (30) hours and in the second problem a more defined superiority is estimated in that the computer solution will require approximately ten (10) minutes versus an estimated sixty (60) hours by hand. However, this comparison does not depict the true time

picture and the long tedious hours of program writing and ever present "debugging" or program correction must be considered. Although the programming time varies greatly with the programmer's familiarity with the problem, computer and also, with the nature of the problem itself; in general the programming time and the time required for one hand calculation are roughly commensurate. The authors estimate that a practicing naval architect very familiar with the proposed problem and experienced in programming could program problem one in twenty (20) hours and problem two in forty (40) hours.

The "debugging" time for each problem would require another ten (10) hours. The fact that the authors, unfamiliar with both the problem and computer, required six times that amount of time indicates that experienced personnel are a very important application factor. In the present case problem understanding and organization were responsible for the greatest loss of time. As a general statement it can be said that for an engineer to properly program a particular problem, his knowledge of that problem must be more thorough than that required for hand calculations. Not only must he know the individual steps in the problem, but also must predict the effect of each step upon the following step and the general value of the numbers generated.

Also, the authors found that one programmer working alone is just as effective as several working together on the same problem. The reason for this is the necessity for a program to follow a single trend of thought and the exact accounting required.

To provide a more complete time description of programming, the nature of the proposed problem should be analyzed. Problem solutions that involve repetition of the same equations will tend to have a much shorter programming time. For instance the time required to program problem one for 40 spans of shafting would be only slightly longer than that required to program 4 spans. Also, the program required to design the web frame by cycling and altering the scantlings is little longer than the program for check calculations.

After the solution of one particular problem by a computer a general program will find further use in solving other similar problems. The programs written for this thesis are reasonably general and the limitations stated in the results are not of serious damage to the program. The limitation of problem one to four shaft spans in a reasonable engineering division in that propeller excited whirling vibration amplitudes beyond span four are so small that their effect on the end fixity of span four is insignificant. In problem two the limitations were imposed to save storage space and reduce the complexity of the program. This coincides with the authors' opinions that for engineering applications several simple programs are easier and faster to handle and program than one complex all purpose program. For instance, web frames are normally constructed symmetrically, 25 points should properly define most normal web shapes and to have a station at each major load or redundant is reasonable. The design hydrostatic head is normally above the maindeck and waterloads are normally considered a constant value along the deck. While the listed position of the ship is an important consideration,

modern naval architects consider the upright position for practical calculations and should the listed condition become necessary for research calculations, rotation formulas and non-symmetrical water loadings must be incorporated into the program. To change stanchions and add decks as redundant supports major alteration of integration procedures would be required.

A general program is useful in design and research to compare and generate great quantities of data and to test the results of slight alterations upon a major problem. For instance, program one could analyze and compare the whirling frequencies of hundreds of ships in a relatively short time or the effects of propeller weight, fixity and blade number may be determined for numerous combinations of values. Problem two would find use in generating design schantlings for various load and size variations such as those found in classification society publications. As a sub-routine in conjunction with a more complex program the stiffness of web frames relative to transverse bulkheads could be determined by application of the theory of beams on elastic foundations. By reiteration of calculations under varying loads the variant or impactive loadings may be analyzed. Since the longest time consumed in a program is in the program writing, problem repetition increases the efficiency of the computer application.

To be feasible for engineering calculations the computer must save time, money and increase the effectiveness of the engineers it aids. Therefore, the computer must accept numbers of engineering magnitude and quantity in a convenient form. The coded instructions must be straightforward

and have names descriptive of their use. Also, the generated results must be presented in such a manner that wide spread publication is possible. Whirlwind I and some commercially available machines will accept decimal digits of sufficient length and quantity to perform most practical engineering and research problems. Of extreme importance is the necessity of maintaining a large library of sub-routines capable of performing such calculations as $\sin^{-1}\theta$, $\sqrt{X}$, etc. Frequently it is desirable to purchase the services of an experienced programmer to act as a consultant when first using a computer.

In computer application there exists two basic schools of thought. One group thinks that problems should be programmed by experts who perform no other function than programming. In this case the engineer presents the problem to the programmer and at some later time is given a solution. The other group states that a computer is best utilized by having engineers familiar with the problem effect the programming. While there exists a middle road somewhere between the two extremes, the authors are of the opinion that engineers should program the computer. This performs two useful functions for the profession as a whole. One, the programmer can make the necessary engineering decisions to adapt the problem more successfully and secondly, the engineer becomes more aware of possible computer applications in his field.

The qualities required of a programmer are no more exacting than those required of a good naval architect. He must have almost infinite patience, imagination, ingenuity, good ability to organize problems and a good background in both theoretical and numerical methods

of mathematics. The work is tedious and all instructions must be perfect since the machine will generate wrong answers as fast as correct ones. Digital computers are often referred to as "brains," but nothing could be more incorrect in that thought is impossible. Actually a computer more nearly resembles a desk calculator or an abacus which operates at a high rate of speed. Imagination and ingenuity are so necessary to produce a workable, general program that many commercial computing companies obtain their programmers from chess clubs, cross-word puzzle enthusiasts and other hobbies where deep concentration and original thought are required.

The future of digital computers in naval architecture appears very promising from both the research and practical viewpoints. In research they can be used for the rapid assimilation and processing of large quantities of technical data and for the solution of problems that require an inordinate amount of time to calculate by hand. Typical examples of the data processing type of problem would be a comparison of stability among several different vessels and other similar problems involving statistical analysis to establish design criteria. Since the same program may be used to solve a number of similar problems, design data in the form of charts and tables can be generated for the grillage beam analysis of decks and other complex problems. Such a procedure permits the determination and testing of important parameters for later application to specific designs.

For specific design applications computers may be used to effect large savings in time and labor. This is possible because the computer can approach more closely an optimum design with little increase in

computing time and expenditure of effort. In this category of application are midship section design, transverse framing design and flight deck bents. In addition, refinements intheory and in the extent of calculations can also be utilized to a greater degree than practical by hand. Examples of these refinements are the use of grillage beam analysis for decks and bulkheads, the performance of stress calculations for a ship in drydock, design of propellers by circulation theory, and the investigation of submarine dynamical stability. In addition to design calculations a digital computer can be applied very readily to scheduling and accounting problems. In shipbuilding this system can be used in determining the weight and center of gravity of a ship as it is being built. Another possibility is merchant ship cargo arrangement.

Theses present an opportunity for wide and varied use of digital computers. In this application the computer should be used as an aid and not as the general subject. A student attempting a problem in which the magnitude of the calculations is the dominant factor should consider computer aid. A desireable arrangement is to have a team with one member learning the problem and another member learning the computer. In this manner both can derive maximum benefit from the thesis and a larger contribution to the profession can be made. Since computers are becoming more widely used, familiarity with their capabilities may be of considerable future value to the student.

CONCLUSIONS

1. Digital computers are applicable to naval architecture problems.

2. The average naval architect has sufficient background to program a digital computer.

3. Some general requirements of a programmer are:

    a. They should have a complete engineering understanding of the problem to be programmed.

    b. Familiarity with numerical methods of mathematical processes is necessary.

    c. They should be amenable to tedious work.

4. The problem to be programmed must be suitable to computers since it may take longer to program than to determine one solution by hand.

5. One programmer can work faster than two or more.

6. In general the limitations imposed on a problem are not serious and are no more restrictive than those in hand calculations.

7. Complete generality of a program is not always feasible.

8. For engineering applications the following features of computers are necessary:

    a. Computer word-length should be able to handle engineering numbers.

    b. Library of sub-routines should be available.

    c. Computer should be easy to program.

RECOMMENDATIONS

1. Digital computers should be used to solve naval architectural problems.

2. Digital computers should be used in theses and research problems.

3. Any future thesis should consider the computer as an aid in the solution of a specific problem and not applicability of computers to a general field.

4. For engineering applications the programmer should have;

    a. good engineering understanding of his field;

    b. knowledge of numerical methods;

    c. organizational qualities and a great deal of ingenuity;

    d. a working knowledge of the computer utilized.

Appendix A

Supplementary Introduction

Supplementary Introduction

A computer program is a series of logical instructions telling the computer what mathematical operations are to be performed on the data. Thus there are two groups of inputs, the data and the instructions. The data fed into the computer is stored in the core memory. Each number or piece of data is stored in a register or "cell" the location of which is designated by a number called the address of that register. After all the data is stored the instructions are stored in the unused portion of the core memory. The instructions are stored in sequence and will be performed in the order in which they are stored. No unused registers are permitted to interrupt the storage as these will stop the computer. The programmer may wish to know the address of key instructions such as the one that starts the computation process. He may assign an address to these instructions or allow the computer to do so, as explained later.

The instructions given to the computer consist of two parts, the operation and address sections. The operation section is first and uses letters to tell the computer what mathematical operation is to be performed. The address section gives the address of the register containing the data on which the operation is to be performed. The instructions recognized by Whirlwind I are listed in the glossary.

When writing a program for a digital computer, there are several useful devices that simplify the procedure. The programming devices described below apply to Whirlwind I and may or may not apply to other computers.

Probably the most useful device is a floating address. A floating address or flad is used to eliminate the necessity of referring

to the absolute register address in the core memory when writing the program. At the beginning of a program the inputs or key instructions on which mathematical operations are to be performed are given floating addresses. These addresses consist of a letter and a number, for example a1,a2 etc. Any letter except O and L may be used and the sum of all the numbers behind the letters may not exceed 255. In writing the program, then, the flad is used in the address section of the instruction to represent the absolute address. The computer will assign absolute addresses or register numbers, to these flads unless this is done by the programmer. For example, if a1 is the first flad in the program, the computer will assign it to register 32. If, however, the programmer wants a1 in the register 130, he writes 130/a1 and the computer will place a1 in register 130. A table is usually produced by the computer showing absolute addresses assigned. It should be remembered that a flad can have only one value in any one program.

Another useful device is preset parameters. These are numbers other than data that are used in the program. Preset parameters are frequently used to designate the number of times a computation is to be repeated. They differ from flads in that they may have any absolute value desired whereas flads must have the absolute address of a register. Preset parameters must be assigned a value before they are used and they will retain this value until it is specifically changed. Preset parameters are designated by two letters and a number. The first letter must be p, u or z and the second letter and the number may be anything, except the letters o and l cannot be used.

In writing a program for a digital computer subroutines are very helpful. Basically there are two distinct types of subroutines which, for lack of a better name, shall be called internal and external. Internal subroutines are those performed automatically by the computer upon receipt of a single instruction. An example of an internal subroutine is the group of output instructions listed in the glossary. Each of these instructions will cause the computer to go through a certain predetermined procedure without any further information from the programmer. External subroutines are further divided into two categories; one category is designated library subroutines and are perfectly general for any program. The other external subroutines are groups of instructions that perform a repetitive section of a particular program. Library subroutines are groups of instructions usually written by an expert programmer for the purpose of performing a particular mathematical operation. They may be an integral part of the main program or they may merely serve as an auxiliary program. Examples of these external library subroutines are groups of instructions used to determine the square root of a number, trigonometric and hyperbolic functions of angles and the solutions to simultaneous equations. Most computer installations have libraries of subroutines available for programmers. These are written quite arbitrarily by using relative addresses and can be used with any main program.

There are some rules that must be followed when using subroutines. The main program must be interrupted to call the subroutine into use. After the subroutine has performed its function, it must direct the control element back to the proper instruction in the main program. An example

of a subroutine follows:

Major program

ica a2

f6, isp g3 -- This instruction directs control to follow the instruction in the register designated by g3.

SUB-ROUTINE

g3, ita g3 plus 20 --- This instruction places the address contained in the control element in g3 plus 20 and adds one to that address. In this example the address contained in the control element is f6.

iad t6

more instructions

" "

" "

" "

g3 plus 20, isp f6 plus 1 -- The address of the isp instruction was supplied by the ita instruction at the beginning of the subroutine.

f6 plus 1, iad a3

The authors do not wish to imply that a program should consist of a series of subroutines, but they are very useful in programs that perform similar operations many times throughout the problem.

The numbers usually encountered in engineering are too large to be stored in one register which, it will be recalled, is 16-binary or about 4 decimal digits long. To accommodate these larger numbers a technique called floating point arithmatic is used. Two consecutive registers, giving 32 binary digits available for each number, are used to replace the single register. Some of these 32 digits are used to record the actual number and some to locate the decimal point. In this manner the range of significant digits can be increased by restricting the number of digits used to locate the decimal point. In the binary system the decimal point is written as some power of 2 and usually 6 binary digits are used to express this power. Since the first digit of each register is used for the sign of the quantity in that register, in this case the sign of the second register is the sign of the exponent of 2. Twenty-four digits are left to express the significant number. This particular distribution of binary digits is referred to as the (24.6) system and can handle numbers equivalent to eight decimal digits with exponents up to 10^{18}. Other systems are available and the size of the numbers in the problem determines which one should be used.

In order to manipulate these two register numbers, an interpretive mode has been internally programmed to function as a part of Whirlwind I. All instructions that refer to double length registers are preceded by an i. If calculations or operations are to be performed on single length registers, the same instructions may be used without the i preceding. Hence there are two modes of calculation; interpretive for double register length numbers and whirlwind for single length register

numbers. It is possible to pass from the whirlwind mode to the interpretive mode by use of the instruction IN and to reverse the direction by use of the instruction OUT.

GLOSSARY OF INSTRUCTIONS

TERM	DEFINITION
ica x	clear MRA and add contents of register x.
ics x	clear MRA and subtract contents of register x.
iad x	add contents of register x to what is in MRA.
isu x	subtract contents of register x from what is in MRA.
imr x	multiply what is in MRA by the contents of register x and round off product to fifteen digits.
idv x	divide contents of MRA by the contents of register x.
its x	transfer the contents of the MRA to register x losing what was previously in register x. The MRA remains unchanged.
iex x	exchange the contents of the MRA with the contents of register x.
isp x	take the next instruction from register x. Does not affect the contents of the MRA. An unconditional instruction used to break the sequence of operations.
icp x	if the contents of the MRA are negative, take the next instruction from register x and continue from there. If the contents of the MRA are positive, take the next instruction in sequence. A conditional instruction used to break the sequence of operations.

<u>Glossary of Instructions</u> (Continued)

TERM	DEFINITION
isc x	select counter number x. Without this instruction counter zero will be used whenever +C appears.
icr x	cycle reset. Sets index register of counter to zero and criterion register to x.
ict x	cycle transfer. Increases contents of index register by one. If contents of index register greater or equal to contents of criterion register, set index register to zero and do next instruction in sequence. If contents of index register less than contents of criterion register, take next instruction from register x.
ici x	increase the contents of index register by number x.
icd x	decrease the contents of index register by number x.
iti x	transfer the right eleven digits of the index register into the right eleven digits of register x.
iat x	add contents of index register to the contents of register x and store the result in the index register and register x.
ita x	replace the address section of the instruction in register x with the address that is one more than the address of the register containing the last <u>isp</u> or <u>icp</u> if the contents of the MRA are negative.

Glossary of Instructions (Continued)

TERM	DEFINITION
iTOA	record the contents of MRA on direct printer (typewriter).
iMOA	record the contents of MRA on magnetic tape for delayed printing.
iSOA	record the contents of MRA on oscilloscope for photographing.
iFOR	this instruction provides an automatic device for obtaining a suitable layout of output data in columns, lines or blocks.

Note: The above output instructions are usually followed by a series of letters and numbers that indicate the desired form and arrangement of the output.

Appendix B
Details of Procedure

Details of Program for Determining the Whirling Frequencies of Propeller Shafts

The first step in programming this problem is to put the numerical values of various quantities into the computer. This is done by the use of floating addresses, or "flads." The proper use and function of flads is explained in Appendix A.

The following table lists the flads, the quantity and the values used. Figure II defines the symbols and nomenclature.

a1, L_0 = 77" - length of tail section.

a2, L_1 = 513.6" - length of inboard sections.

L_2 = 576.0"

L_3 = 544.6"

b1, $E_0I_0 = 17.4 \times 10^{10}$ lb-in^2 - E times moment of inertia of tail section.

b2, $E_1I_1 = 13.7 \times 10^{10}$ lb-in^2 - E times moment of inertia of inboard sections.

$E_2I_2 = 12.4 \times 10^{10}$ lb-in^2

$E_3I_3 = 12.4 \times 10^{10}$ lb-in^2

c1, W_p = 47,815 lb - weight of propeller

c2, γ_1 = .284 lb/in^3 - specific weight of material used in inboard shaft sections.

γ_2 = .284 lb/in^3

γ_3 = .284 lb/in^3

d1, A_1 = 193.5 in^2 - average area of shaft cross section for each span.

A_2 = 174.5 in^2

A_3 = 174.5 in^2

d2, 3 - number of shaft spans used.

d3, 135 - number of increments of β desired to be used. β is increased by increments of 2 degrees.

e3, $(\frac{1}{2} + \frac{1}{q})$ $q = 6$

$(\frac{1}{2} - \frac{1}{q})$ $q = 6$ - q is the order of frequency being investigated. Plus sign is used for backward precession and the minus sign for forward precession.

$(\frac{1}{2} - \frac{1}{q})$ $q = 1$

e4, $J = 244.0 \times 10^6$ - polar moment of inertia of propeller and entrained water.

e6, $\beta_1 = 90$ - initial starting value of β_1, in degrees.

The above listed flads are the only ones that must be changed in order to adapt this program to another problem. In order to accomplish this change it is merely necessary to add a tape with the correct values at the end of the program.

The following table lists flads that contain constants which will remain unchanged for every problem:

e1,	$\pi = 3.1416$
e2,	180
e5,	$g = 386$ in-sec^2
e7,	β_1 = current value of β. (β_1 + increment)
e8,	$(\frac{\pi}{180})^4$
e9,	$\frac{\pi}{(180)^2}$
e10,	2
e11,	1
e12,	3
e13,	4

A block of registers consisting of f and g flads has been set aside as intermediate storage. This is necessary to enable the computer to calculate quantities, store them temporarily and use them later in the program. Another group of registers consisting of t and u flads are set aside for temporary storage. These quantities are used once and then discarded.

The last group of flads used is the h and m group. These are used to control the program by assigning key instructions to them.

The outputs from this program will consist of a series of frequencies and corresponding end moments. These values will be arranged in two columns with the frequency corresponding to the moment that appears on the same line. It is very important to include the sign of the moment, for we are more interested in the point where the moment passes through zero than the actual values obtained.

In performing certain routine arithmetical operations, such as finding the square root, use was made of the sub-routine library in the computer laboratory. These sub-routines are very reliable and save considerable time when programming.

The actual orders used for programming this problem follow. The short paragraph at the beginning of each section explains briefly the function of the orders in that section.

These three orders place the sub-routines for square root, sine-cosine and sinh-cosh at the beginning of the program. This is very desirable as it eliminates any confusion with the main program.

Order

S1, LSR, FU8

S2, LSR, FU4a

S3, LSR, FU5

Put in flad assignments a1 through g10 as previously noted.

These orders are assigning values of 3, 2, 3 in the flads M1, M2, M3, respectively, the function of these flads is to set the cycle counter criterion registers to a predetermined value. The operation is done in WW1 since the numbers are single register numbers. The last order is used to enter the CS mode.

Order	Input to MRA	In MRA	Transfer from MRA
h1, ca, d2	3	3	
td, m1		3	3
td, m3		3	3
su, e11	-1	2	
td, m2		2	2
IN			

This group of orders will calculate the weights of each shaft span and store the results in f1. The first order says that the operation is to be repeated three times. The +C at the end of the next four orders is to permit the address section of the instruction to be increased by two registers on each cycle thus allowing three different

weights to be calculated by the same set of orders. The last instruction is necessary to return control to the first instruction at the end of each calculation, to increase the address of each instruction by two registers after each operation, and to pass control to the next order when the operation has been performed the number of times specified by the first order.

Order	Input to MRA	In MRA	Transfer from MRA
ml, icr			
h2, ica, c2+c	γ_1	γ_1	
imr, a2+c	$\times\ L_1$	$L_1 \times \gamma_1$	
imr, dl+c	$\times\ A_1$	$L_1 \times \gamma_1 \times A_1$	
its, fl+c		W_1	W_1

This group of orders will calculate C_a and store the results in f2. The cycle will be performed three times since the order ml, icr is still effective.

Order	Input to MRA	In MRA	Transfer from MRA
h3, ica, b2+c	$E_1 I_1$	$E_1 I_1$	
idv, a2+c	$\div\ L_1$	$\frac{E_1 I_1}{L_1}$	
its, f2+c		$\frac{E_1 I_1}{L_1}$	C_a
ict, h3			

This group of orders will calculate C_d for each span and store the results in f3. The cycle will be repeated three times since the order ml, icr is still effective.

Order	Input to MRA	In MRA	Transfer from MRA
h4, ica, f2+c	$\frac{E_1 I_1}{L_1}$	$\frac{E_1 I_1}{L_1}$	
idv, a2+c	$\div L_1$	$\frac{E_1 I_1}{L_1^2}$	
idv, a2+c	$\div L_1$	$\frac{E_1 I_1}{L_1^3}$	
idv, f1+c	$\div W_1$	$\frac{E_1 I_1}{W_1 L_1^3}$	
its, f3+c		$\frac{E_1 I_1}{W_1 L_1^3}$	C_d
ict, h4			

This group of orders will calculate the constant $\pi/(180)^2$ and store the result in e9. This operation will only be performed once as no cycle is indicated.

Order	Input to MRA	In MRA	Transfer from MRA
ica, e1	π	π	
idv, e2	$\div$ 180	$\pi/180$	
idv, e2	$\div$ 180	$\pi/(180)^2$	
its, e9		$\pi/(180)^2$	$\pi/(180)^2$

This group of orders will calculate the constant $(\pi/180)^4$ and store the result in e8. The device used here is that when a number is transferred from the MRA to a register the MRA retains the number. The fourth power is formed by multiplying the number in the MRA by the number that was transferred which is the same as squaring the number in the MRA, in this case $(\pi/180)^2$.

Order	Input to MRA	In MRA	Transfer from MRA
imr, e1	$\times$ π	$(\pi/180)^2$	
its, e8		$(\pi/180)^2$	$(\pi/180)^2$
imr, e8	$\times$ $(\pi/180)^2$	$(\pi/180)^4$	
its, e8		$(\pi/180)^4$	$(\pi/180)^4$

This group of orders will calculate C_w and store the result in f4.

Order	Input to MRA	In MRA	Transfer from MRA
ica, f3	$\frac{E_1I_1}{W_1L_1^3}$	$\frac{E_1I_1}{W_1L_1^3}$	
imr, c1	$\times\ W_p$	$\frac{W_pE_1I_1}{W_1L_1^3}$	
imr, a1	$\times\ L_0$	$\frac{W_pL_0E_1I_1}{W_1L_1^3}$	
imr, a1	$\times\ L_0$	$\frac{W_pL_0^2E_1I_1}{W_1L_1^3}$	
imr, a1	$\times\ L_0$	$\frac{W_pL_0^3E_1I_1}{W_1L_1^3}$	
idv, b1	$\div\ E_0I_0$	$\frac{W_pL_0^3E_1I_1}{W_1L_1^3E_0I_0}$	
imr, e8	$\times\ (\frac{\pi}{180})^4$	$\frac{W_pL_0^3E_1I_1}{W_1L_1^3E_0I_0}(\frac{\pi}{180})^4$	
its, f4		$\frac{W_pL_0^3E_1I_1}{W_1L_1^3E_0I_0}(\frac{\pi}{180})^4$	C_w

This group of orders will calculate C_f and store the result in f6. In this operation the square root sub-routine is used. The third order is used to enter this sub-routine, which is in the Whirlwind mode, requiring the IN order to return to the CS mode once the square root has been calculated.

Order	Input to MRA	In MRA	Transfer from MRA
ica, e5	g	g	
imr, f3	$\times \dfrac{E_1 I_1}{W_1 L_1^3}$	$\dfrac{E_1 I_1 g}{W_1 L_1^3}$	
sp, s1		$\dfrac{E_1 I_1 g}{W_1 L_1^3}$	
IN		$\dfrac{E_1 I_1 g}{W_1 L_1^3}$	
imr, e9	$\times \dfrac{\pi}{(180)^2}$	$\dfrac{\pi}{(180)^2}\sqrt{\dfrac{E_1 I_1 g}{W_1 L_1^3}}$	
idv, e10	$\div 2$	$\dfrac{\pi}{2(180)^2}\sqrt{\dfrac{E_1 I_1 g}{W_1 L_1^3}}$	
its, f6		$\dfrac{\pi}{2(180)^2}\sqrt{\dfrac{E_1 I_1 g}{W_1 L_1^3}}$	C_f

This group of orders will calculate C_β and store the result in f7. The operation is performed twice, since m2 is 2, because this constant is used to determine β_2 and β_3. If more spans were used this operation would be performed a number of times equal to two less than the number of spans. The square root sub-routine is used twice in succession here to form the fourth root of a number.

Order	Input to MRA	In MRA	Transfer from MRA
m2, icr			
h5, ica, f3	$\frac{E_1 I_1}{W_1 L_1^3}$	$\frac{E_1 I_1}{W_1 L_1^3}$	
idv, f3+2+c	$\div \frac{E_2 I_2}{W_2 L_2^3}$	$\frac{E_1 I_1 W_2 L_2^3}{W_1 L_1^3 E_2 I_2}$	
sp, sl			
sp, sl			
IN		$\sqrt[4]{\frac{E_1 I_1 W_2 L_2^3}{W_1 L_1^3 E_2 I_2}}$	
its, f7+c		$\sqrt[4]{\frac{E_1 I_1 W_2 L_2^3}{W_1 L_1^3 E_2 I_2}}$	C_β
ict, h5			

This group of orders will calculate C_j and store the result in f5. This operation is to be performed three times as indicated by the first order. The flad ml was not used here because the number of times this operation is performed depends on the number of vibrational orders being investigated and is independent of the number of spans. Usually three orders of vibration will be investigated, (synchronous, forward and backward precession). The flad h6 is the beginning of

the first loop of the program. This means that when the program has been run through once it will automatically come back to h6 and do the entire program again using the second value of e3. This loop will be performed three times as indicated by the first instruction.

Order	Input to MRA	In MRA	Transfer from MRA
icr, 3			
h6, ica, f3	$\frac{E_1 I_1}{W_1 L_1^3}$	$\frac{E_1 I_1}{W_1 L_1^3}$	
imr, e4	$\times J$	$\frac{E_1 I_1 J}{W_1 L_1^3}$	
imr, a1	$\times L_0$	$\frac{E_1 I_1 J L_0}{W_1 L_1^3}$	
idv, b1	$\div E_0 I_0$	$\frac{E_1 I_1 J L_0}{E_0 I_0 W_1 L_1^3}$	
imr, e3+c	$\times (\frac{1}{2} + \frac{1}{q})$	$\frac{E_1 I_1 J L_0}{E_0 I_0 W_1 L_1^3} (\frac{1}{2} + \frac{1}{q})$	
imr, e8	$\times (\frac{\pi}{180})^4$	$\frac{E_1 I_1 J L_0}{E_0 I_0 W_1 L_1^3} (\frac{1}{2} + \frac{1}{q}) (\frac{\pi}{180})^4$	
its, f5		$\frac{E_1 I_1 J L_0}{E_0 I_0 W_1 L_1^3} (\frac{1}{2} + \frac{1}{q}) (\frac{\pi}{180})^4$	C_j

This group of orders assigns a value to the flad m4. The value used is that contained in d3 which for this problem was 135. This number was selected because we wanted β to vary from 90° to 360° in as small an increment as possible to increase the accuracy. Due to limitations on the magnetic tape output the smallest increment feasible was 2°. The first instruction is used to select the Whirlwind mode since the transfer of digits as indicated by the third instruction cannot be performed in the cs mode. The fourth order is used to return to the cs mode before proceeding with the remainder of the program.

The last instruction is used to select a new cycle counter. This instruction permits a loop within a loop to be performed. In the preceeding group of instructions counter zero was used and is stepped once each time the sequence is performed, but a different counter is used to allow the following sequence to be performed, and counted, a specified number of times without interfering with the previous counter.

Order	Input to MRA	In MRA	Transfer from MRA
OUT			
ca, d3	135	135	
td, m4		135	135
IN			
is, cl			

This group of orders will calculate the frequency and print the result on the magnetic tape output device. This operation will be

performed 135 times, indicated by the first order, for each cycle of the main program. The second through the fifth orders calculate β^2 and β^4 and store them in g1 and g2 respectively. The frequency is then found by multiplying C_f by β^2. The last instruction is an order to the computer selecting the output device and giving the information necessary to print the frequencies in a column, the number of digits desired, etc.

Order	Input to MRA	In MRA	Transfer from MRA
m4, icr			
h7, ica, e6	90°	90°	
imr, e6	$\times\ 90^\circ$	$(90^\circ)^2$	
its, g1		$(90^\circ)^2$	β_2
imr, g1	$\times\ (90^\circ)^2$	$(90^\circ)^4$	
its, g2		$(90^\circ)^4$	β_4
ica, f6	$\frac{\pi}{2(180)^2}\sqrt{\frac{E_1 I_1 g}{W_1 L_1^3}}$	$\frac{\pi}{2(180)^2}\sqrt{\frac{E_1 I_1 g}{W_1 L_1^3}}$	
imr, g1	$\times\ (90^\circ)^2$	$\frac{\pi(90)^2}{2(180)^2}\sqrt{\frac{E_1 I_1 g}{W_1 L_1^3}}$	

imoap 1234.56ssss

This group of orders will calculate the moment at the inboard end of the tail shaft, m_{01}, and store the results in g5. This operation will also be performed 135 times for each cycle of the main program.

ϕ_W and ϕ_J, both functions of β are computed first and stored in g3 and g4 respectively. Using the formula in the flow-chart they are combined to calculate m_{01}. It should be noted that this and the preceeding calculations do not require more than two double length registers to store the results. In the frequency calculations the results are printed out as soon as they are obtained. Here the results stored in g5 are used immediately in the subsequent calculations after which they are no longer desired. Therefore, the m_{01} calculated is lost as each succeeding moment is determined.

Order	Input to MRA	In MRA	Transfer from MRA
ica f4	$\frac{W_p L_0^3 E_1 I_1}{W_1 L_1^3 E_0 I_0}\left(\frac{\pi}{180}\right)^4$	$\frac{W_p L_0^3 E_1 I_1}{W_1 L_1^3 E_0 I_0}\left(\frac{\pi}{180}\right)^4$	
imr g2	β^4	$\frac{W_p L_0^3 E_1 I_1}{W_1 L_1^3 E_0 I_0}\left(\frac{\pi\beta}{180}\right)^4$	
its g3		$\frac{W_p L_1^3 E_1 I_1}{W_1 L_1^3 E_0 I_0}\left(\frac{\pi\beta}{180}\right)^4$	ϕ_W
ica f5	$\frac{E_1 I_1 J L_0}{E_0 I_0 W_1 L_1^3}\left(\frac{1}{2}+\frac{1}{q}\right)\left(\frac{\pi}{180}\right)^4$	$\frac{E_1 I_1 J L_0}{E_0 I_0 W_1 L_1^3}\left(\frac{1}{2}+\frac{1}{q}\right)\left(\frac{\pi}{180}\right)^4$	
imr e6	β	$\frac{E_1 I_1 J L_0}{E_0 I_0 W_1 L_1^3}\left(\frac{1}{2}+\frac{1}{q}\right)\left(\frac{\pi}{180}\right)^4\beta$	
its g4		$\frac{E_1 I_1 J L_0}{E_0 I_0 W_1 L_1^3}\left(\frac{1}{2}+\frac{1}{q}\right)\left(\frac{\pi}{180}\right)^4\beta$	ϕ_J

Order	Input to MRA	In MRA	Transfer from MRA
	(continued)		
ica g3	ϕ_W	ϕ_W	
idv e12	$\div 3$	$\frac{\phi_W}{3}$	
its t1		$\frac{\phi_W}{3}$	$\frac{\phi_W}{3}$
idv e13	$\div 4$	$\frac{\phi_W}{12}$	
imr g4	$\times \phi_J$	$\frac{\phi_W \phi_J}{12}$	
iad 1h9	$+ 1$	$1 + \frac{\phi_W \phi_J}{12}$	
isu t1	$- \frac{\phi_W}{3}$	$1 + \frac{\phi_W \phi_J}{12} - \frac{\phi_W}{3}$	
isu g4	$- \phi_J$	$1 + \frac{\phi_W \phi_J}{12} - \frac{\phi_W}{3} - \phi_J$	
its t2		$1 + \frac{\phi_W \phi_J}{12} - \frac{\phi_W}{3} - \phi_J$	$1 + \frac{\phi_W \phi_J}{12} - \frac{\phi_W}{3} - \phi_J$
ica t1	$\frac{\phi_W}{3}$	$\frac{\phi_W}{3}$	
imr g4	$\times \phi_J$	$\frac{\phi_W \phi_J}{3}$	
isu g4	$- \phi_J$	$\frac{\phi_W \phi_J}{3} - \phi_J$	

Order	Input to MRA	In MRA	Transfer from MRA
	(continued)		
isu g3	$-\phi_W$	$\frac{\phi_W\phi_J}{3} - \phi_J - \phi_W$	
idv t2	$\div 1 + \frac{\phi_W\phi_J}{12} - \frac{\phi_W}{3} - \phi_J$	$\dfrac{\frac{\phi_W\phi_J}{3} - \phi_J - \phi_W}{1 + \frac{\phi_W\phi_J}{12} - \frac{\phi_W}{3} - \phi_J}$	
imr b1	$\times E_0I_0$	$E_0I_0\left[\dfrac{\frac{\phi_W\phi_J}{3} - \phi_J - \phi_W}{1 + \frac{\phi_W\phi_J}{12} - \frac{\phi_W}{3} - \phi_J}\right]$	
idv a1	$\div L_0$	$\frac{E_0I_0}{L_0}\left[\dfrac{\frac{\phi_W\phi_J}{3} - \phi_J - \phi_W}{1 + \frac{\phi_W\phi_J}{12} - \frac{\phi_W}{3} - \phi_J}\right]$	
its g5		$\frac{E_0I_0}{L_0}\left[\dfrac{\frac{\phi_W\phi_J}{3} - \phi_J - \phi_W}{1 + \frac{\phi_W\phi_J}{12} - \frac{\phi_W}{3} - \phi_J}\right]$	m_{01}

This group of orders will first convert the value of β currently stored in e6 from degrees into radians and store the result in e7. The last two orders will place the initial value of θ_{01}, which is assumed as unity, in g9.

Order	Input to MRA	In MRA	Transfer from MRA
ica e6	β	β	
imr e1	π	$\pi\beta$	
idv e2	180	$\frac{\pi\beta}{180}$	
its e7		$\frac{\pi\beta}{180}$	$\frac{\pi\beta}{180}$
ica 1h9	1	1	
its g9		1	θ_{01}

This group of orders will calculate various parameters, such as cos β, sin β and store them temporarily for future use in the calculation of end moments. The first instruction selects a third counter to be used for this and subsequent calculations. This is done for the same reason as before, to permit this sequence to cycle three times, once for each inboard span, without affecting the cycle count of the previous loop. The second instruction sets the number of times the loop is to cycle. This number equals the number of spans since m3 takes its valud from d3 which is the flad assigned for the number of spans. The manner in which the subroutines are utilized is shown here and their advantage becomes evident.

Order	Input to MRA	In MRA	Transfer from MRA
isc 2			
m3, icr			
h8, ica e7	β_1	β_1	
isp s2		$\cos\beta_1$	
its u1		$\cos\beta_1$	$\cos\beta_1$
ica e7	β_1	β_1	
isp 1s2		$\sin\beta_1$	
its u2		$\sin\beta_1$	$\sin\beta_1$
ica e7	β_1	β_1	
isp s3		$\sinh\beta_1$	
its u3		$\sinh\beta_1$	$\sinh\beta_1$
ica e7	β_1	β_1	
isp 5s3		$\cosh\beta_1$	
its u4		$\cosh\beta_1$	$\cosh\beta_1$
ica u3	$\sinh\beta_1$	$\sinh\beta_1$	
isu u2	$-\sin\beta_1$	$\sinh\beta_1-\sin\beta_1$	
its u5		$\sinh\beta_1-\sin\beta_1$	$\sinh\beta_1-\sin\beta_1$
ica u1	$\cos\beta_1$	$\cos\beta_1$	
imr u3	$\times\sinh\beta_1$	$\cos\beta_1\sinh\beta_1$	
its u6		$\cos\beta_1\sinh\beta_1$	$\cos\beta_1\sinh\beta_1$

This group of orders will calculate the parameters s1, s2, s3, and store the results in g6, g7, and g8 respectively. This operation will be repeated three times, once for each span, since the first two orders of the previous section are still in effect.

<u>Order</u>	<u>Input to MRA</u>	<u>In MRA</u>	<u>Transfer from MRA</u>
ica u2	$\sin \beta_1$	$\sin \beta_1$	
imr u4	$\times \cosh \beta_1$	$\sin \beta_1 \cosh \beta_1$	
isu u6	$-\cos \beta_1 \sinh \beta_1$	$\sin \beta_1 \cosh \beta_1 - \cos \beta_1 \sinh \beta_1$	
idv u5	$\div \sinh \beta_1 - \sin \beta_1$	$\dfrac{\sin \beta_1 \cosh \beta_1 - \cos \beta_1 \sinh \beta_1}{\sinh \beta_1 - \sin \beta_1}$	
its g6		$\dfrac{\sin \beta_1 \cosh \beta_1 - \cos \beta_1 \sinh \beta_1}{\sinh \beta_1 - \sin \beta_1}$	S_1
ica u3	$\sinh \beta_1$	$\sinh \beta_1$	
isu u2	$-\sin \beta_1$	$\sinh \beta_1 - \sin \beta_1$	
imr e7	$\times \beta_1$	$\beta_1(\sinh \beta_1 - \sin \beta_1)$	
its u5		$\beta_1(\sinh \beta_1 - \sin \beta_1)$	$\beta_1(\sinh \beta_1 - \sin \beta_1)$
ics u1	$-\cos \beta_1$	$-\cos \beta_1$	
imr u4	$\times \cosh \beta_1$	$-\cos \beta_1 \cosh \beta_1$	
iad 1h9	$+1$	$1 - \cos \beta_1 \cosh \beta_1$	
idv u5	$\div \beta_1(\sinh \beta_1 - \sin \beta_1)$	$\dfrac{1 - \cos \beta_1 \cosh \beta_1}{\beta_1(\sinh \beta_1 - \sin \beta_1)}$	

Order	Input to MRA	In MRA	Transfer from MRA
		(continued)	
its g7		$\dfrac{1-\cos\beta_1 \cosh\beta_1}{\beta_1(\sinh\beta_1-\sin\beta_1)}$	S_2
ica u3	$\sinh\beta_1$	$\sinh\beta_1$	
isu u2	$-\sin\beta_1$	$\sinh\beta_1-\sin\beta_1$	
its u5		$\sinh\beta_1-\sin\beta_1$	$\sinh\beta_1-\sin\beta_1$
ica e10	2	2	
imr e7	$\times\beta_1$	$2\beta_1$	
imr u2	$\times\sin\beta_1$	$2\beta_1\sin\beta_1$	
imr u3	$\times\sinh\beta_1$	$2\beta_1\sin\beta_1\sinh\beta_1$	
idv u5	$\div\sinh\beta_1-\sin\beta_1$	$\dfrac{2\beta_1\sin\beta_1\sinh\beta_1}{\sinh\beta_1-\sin\beta_1}$	
its g8		$\dfrac{2\beta_1\sin\beta_1\sinh\beta_1}{\sinh\beta_1-\sin\beta_1}$	S_3

This group of orders will calculate the end moments and the angle of rotation at the inboard end of the shaft selected. The previous results stored in g5, namely m_{01}, and previously calculated values of θ_{01}, s1, s2, s3 are combined into the formulas shown in the flow chart to determine the values at the end of the second section, m_{12}. This process is repeated three times to produce m_{34}, the moment we are looking for. θ_{34} is also determined although it is not utilized.

The method of saving registers that is used in this section should be noted. m_{01} is in g5. As each successive moment is calculated it too is put in g5. The preceeding moment is lost by this process, but it is of no importance since only the final end moment is required.

The last six orders have a different function. The first five of these are utilized to calculate the value of β_2 for the next span which is used in the calculation of the moment and s1, s2, s3. The relation of β and β_2 is shown in the flow chart.

The last order is used to cycle the program back to h8. ict causes the computer to return to h8 and at the same time increases the index of the cycle counter by one. When the index equals the number previously set in the criterion by an icr instruction ict will reset the index to +0 and pass control to the instruction immediately following.

Order	Input to MRA	In MRA	Transfer from MRA
ica g5	m_{01}	m_{01}	
its g10		m_{01}	m_{01}
ics g5	$-m_{01}$	$-m_{01}$	
imr g6	$\times S_1$	$-m_{01}S_1$	
its u1		$-m_{01}S_1$	$-m_{01}S_1$
ics f2+c	$-C_a$	$-C_a$	
imr g8	$\times S_3$	$-C_aS_3$	
imr g9	$\times \theta_{01}$	$-C_aS_3\theta_{01}$	

Order	Input to MRA	In MRA	Transfer from MRA
		(continued)	
iad ul	$-m_{01}S_1$	$-C_aS_3\theta_{01}-m_{01}S_1$	
its g5		$-C_aS_3\theta_{01}-m_{01}S_1$	m_{12}
ics g10	$-m_{01}$	$-m_{01}$	
imr g7	$\times S_2$	$-m_{01}S_2$	
idv f2+c	$\div C_a$	$\frac{-m_{01}S_2}{C_a}$	
isu g6	$-S_1$	$\frac{-m_{01}S_2}{C_a} - S_1$	
its g9		$\frac{-m_{01}S_2}{C_a} - S_1$	θ_{12}
ica f7+c	C_β	C_β	
imr e6	$\times \beta$	$C_\beta \beta$	
imr e1	$\times \pi$	$\pi C_\beta \beta$	
idv e2	$\div 180$	$\frac{\pi}{180} C_\beta \beta$	
its e7		$\frac{\pi}{180} C_\beta \beta$	β_2
ict h8			

This group of orders will print out the contents of g5, which are the moments at the inboard end of the shaft. The first instruction

is used to return the counting of cycles back to the 135. This is done since we want 135 end moments printed, or one for each β value used.

Order	Input to MRA	In MRA	Transfer from MRA
isc 1			
ica g5	m_{34}	m_{34}	
imoa+p 1234.56×10^{-6}c			

This group of orders does several things which will be discussed in the order of their occurance.

The first three orders are used to increase the value of β in e6 by 2° before the next cycle starts. This operation is performed 135 times also, the β starts at 90° and goes to 360° in steps of 2°.

The fourth order is used to break the normal sequence and add a correction before returning to the main program, a process known as patching. The correction added is given below. The first instruction is merely a new flad used to get the number +1.0 in the computer. The second instruction increases the index of counter 1 by one and performs the same function as explained above, namely, permit this part of the program to cycle 135 times. The third and fourth instructions are merely to print a series of zeros in the print out to separate the results into blocks of 135 lines of frequency vs. moment for each order being investigated. The last instruction is to pass control to the next patch.

Order	Input to MRA	In MRA	Transfer from MRA
ica e6	β	β	
iad e10	+2	β+2	
its e6		β+2	β+2
isp 3h9			
isp h12			
ict h6			
h9, i STOP			
START AT h1			
1h91+1.0			
ict h7			
ica 1h9	+1.0	+1.0	
imoa+1234cc			
isp-2h9			

This group of orders will do several things. First it passes control to the flad h12 which introduces the subroutine of resetting the value of β to 90° at the completion of the program for one order. Then counter zero is selected to begin calculations for the next order. The instruction OUT is used to enter the Whirlwind mode and the next three instructions are used to increase the address of 4h6 by two. This is normally done automatically by the use of counters and +c at the end of each instruction. However, difficulty was encountered and this "manual" stepping was used to save time. The last two instructions are used to return to the CS mode and the main program at one instruction before h9.

Order	Input to MRA	In MRA	Transfer from MRA
h11, +90,0			
-2h9/isp h12			
h12, ica h11	+90.0	+90.0	
its e6		+90.0	+90,0
isc 0			
OUT			
ca4h6	285	285	
ade 11	+1	286	
ade 11	+1	287	
ts4h6		287	4h6
IN			
isp h9-1			

The main program is reentered as explained above and the last three instructions listed below are performed. The first increases the index of counter zero by one and when the entire program has been repeated three times passes control to the second instruction which stops the computer.

The last instruction is used to start the calculations at the proper place. It is always the last instruction fed into the computer since the computer scans the entire program, locates the flads and stores the information before it starts. If this instruction were anywhere else the computer would start computing before all the information was fed into it and properly stored.

Order	Input to MRA	In MRA	Transfer from MRA
ict h6			
h9, i STOP			
START AT h1			

PROGRAM OF STRESS CALCULATIONS OF NON-SYMMETRICALLY LOADED TRANSVERSE WEB FRAME

The working program of the web frame stress calculations will consist of a series of sub-routines joined together by a sequence control program (see Figure V). To facilitate programming and program alteration, the instructions and input data were placed in four separate sections and these sections were represented by the flexowriter tape number that contained the instructions on data. Scantling data and other information relating to a particular problem were placed in tape 359-217-100. The sub-routines were placed in 359-217-101, and, the sequence control programs were placed in 359-217-221 and 359-217-222. Calculations for a different though similar ship will require the complete changing of tape 359-217-100. Tape 359-217-101 is general for similar problems. Tapes 359-217-221 and 222 determine the nature of the calculations, that is whether a check calculation or a design calculation will be calculated.

In the instructions for the input data in tape 359-217-100 absolute addresses were assigned to flads. The absolute addresses were necessary for block in, bl out procedures used in the auxiliary storage drum. The use of flads is still retained due to the ease of writing and categorizing letters. The flad and absolute address assignments for storage of generated data were also placed in tape 359-217-101.

The following list of data are the specific input data for a DP type vessel. Due to the quantity of numbers in each ategory, only a sample of the total group is presented below.

fc Tape 359-217-100

(24,6)

32 | x1, +00.00' — Assigns the first value of the x-coordinate of the shell to register 32 which is the first register in the case memory. Note that the coordinates are in feet measured from the origin at the keel centerline.

+3.266'

+6.508'

+9.917

Total of 25 double length numbers which occupy 50 registers.

+0.000 — Value at the main deck centerline.

82 | y1, +00.00' — First value of y-coordinates of the shell.

25 numbers

+26.33 — y-coordinate of main deck centerline.

332 | b1, +24.00 — Value of web depth (d_w) at the origin measured in inches. First value stored in register 332.

25 numbers

+12.00 — Value at main-deck centerline.

282 | b2, +0.3125 — Thickness of web (t_w) measured in inches.

25 numbers

+0.2500

482 | b3, +12.0 — Width of flange (w_f) measured in inches.

25 numbers

4.0

432 | b4, +0.500 — Flange thickness (t_f) measured in inches.

25 numbers

+0.250

382 | b5, +0.7500 — Shell thickness (t_s) in inches.

25 numbers

+0.375

632 e5, -974.0 50 numbers -974.0	Weight and shear loads at each station. The weights are determined in averaging the weight of vessel and shear for one foot of length. The length per foot times the number of feet of girth between stations gives the weight load per station.
932 e2, +25.517	Height of water pressure head. In this problem the design water head was the height of the deck edge.
978 e1, +8.0	Longitudinal distance between web frames. The stresses computed were for the loads on one foot of logitudinal distance. Each web frame is assumed to support the loads imposed in the longitudinal distance between frames.
pa1 = 25	Present parameter which represents the number of stations from the origin deck centerline.
pa2 = 18	Present parameter which represents the number of stations from the origin to the deck edge.
pa3 = 4	Number of stations from the origin to the bottom of the starboard stanchion.
pa4 = 4	Number of stations from the origin to the bottom of port stanchion when measuring counter clockwise.
pa5 = 18	Number of stations between bottom and top of the starboard stanchion.
pa6 = 18	Number of stations between bottom and top of the port stanchion.

The following instructions are the sequence control instructions and serve to utilize various sub-routines to perform the calculations of stresses for a web frame of one particular set of scantlings and load

conditions. To alter the web frame and to produce a rational design, another set of instructions designated tape number 359-217-222 will be required.

fc 359-217-221 (Name of tape)
(24,6)

(Selects number arrangement of double length registers. This arrangement utilizes 24 binary numbers for the mantissa and 6 binary digits for the exponent of the number).

pl, isp g1	g1 forms sin θ, cos θ and Δs
isp g2-2	g2-2 forms horizontal and vertical water loads H_w, V_w.
isp g10-2	g10-2 forms the total vertical loads by summing the values of the weights and vertical water loads.
isp g3	g3 forms sin ϕ and cos ϕ.
isp g4	Forms the reciprocal of the moment of inertia $(1/I_{N.A.})$, of the section (A_t) and distance from the shell to the neutral axis $(d_{N.A.})$.
OUT	The following orders are block out instructions for transferring information from the case memory to the auxiliary drum.
ca c8	2048 (Address of first register of the drum storage block).
si 967	Selects case output routine to the auxiliary drum.
ca c12	800 (Number of registers necessary for storage).
b0 32	(Case memory address of the first register being blocked out).
IN	
isp g6-2	Offsets the x and y coordinates of the neutral axis from the shell coordinates.

isp g1	Forms sin θ and cos θ, and Δs of neutral axis.		
isp g3	Forms sin ϕ, and cos ϕ of neutral axis.		
ica c6	+0.0	+0.0	
its t4			+0.0
its b3			+0.0
isp g7	Forms m/I at each station due to applied loads,		
isp g9	Forms integrals of m_0, p_0, q_0, R and S, into a matrix (See Figure VI).		
isp g23-2	Uses Crout's method to solve the matrix.		
isp g24-1	Alters V and H to include redundants $V-q_0$, $H+p_0$, R+V and V+S.		
ica d1+50	$+m_0$	$+m_0$	
its t4			$+m_0$
imr d3	$1/I_0$	m_0/I_0	
its b3			m_0/I_0
isp g7	Forms moments at each station. This moment includes the effect of the redundants		

OUT

ca c10	2348 - Drum address of the first register of the drum storage.
si 963	Selects "block-in" procedure for transferring data from the drum to the case memory.
ca c17	+150 - Number of registers being "blocked in." Blocks in d_w, t_s and t_f.
bi 332	Address of the first register in the core memory that will receive the first number moved in from the drum.
ca c11	+2748 - Address of the first register of the drum storage.

si 963	Selects "block in" routine from the drum storage.
ca c18	+50 - Blocks in 50 registers of information of $d_{N.A.}$
bi 732	Address of the first register in the core memory that will contain $d_{N.A.}$
IN	
p2, isp g25-1	Forms σ_a, σ_b, σ_f and σ_s for all stations around the girth.

The following instructions, called tape 359-217-222, perform the stress calculations for a web frame for a given set of scantlings and compare the computed stresses with allowable stresses. If the computed stresses do not fall within the range of allowable stresses, then the instructions below will alter the scantlings of the web frame to produce the desired stresses. For this program the scantlings are altered by increasing or decreasing the width of the flange. Notice that tape 359-217-222 repeats all the instructions contained in 359-217-221 and in addition contains a method of altering the flange. While this may seem unnecessarily repetitious, two complete sequence programs were deemed more convenient to handle and less susceptible to error than one partial tape with a connective addition.

fc 359-217-222
(24,6)

p1, isp g1	g1 forms sin θ, cos θ and Δs.
isp g2-2	g2-2 forms V_w and H_w.
isp g10-2	g10-2 forms V_t
isp g3	g3 forms sin ϕ and cos ϕ.
isp g4	g4 forms $1/I_{N.A.}$, A_t, and $d_{N.A.}$
OUT	

ca c8	2048 - Drum Address.		
si 967	Selects drum output routine.		
ca c12	800 - Number of registers being transferred.		
b0 32	Core memory, address of first register being blocked out.		
IN			
isp g6-2	Forms $(x_{N.A.}, y_{N.A.})$.		
isp g1	sin θ, cos θ, and Δs of neutral axis.		
isp g3	sin ϕ and cos ϕ or neutral axis,		
ica c6	+0.0	+0.0	
its t4			+0.0
its b3			+0.0
isp g7	Forms m_n/I at each station		
isp g9	Forms integrals of m_0, p_0, q_0, R and S. (See Figure VI).		
isp g23-2	Matrix solution.		
isp g24-1	Alters loads to include redundants. q_0, p_0, R and S.		
ica d1+50	$+m_0$	$+m_0$	
its t4			$+m_0$
imr d3	$1/I_0$	m_0/I_0	
its b3			m_0/I_0
isp g7	Forms moments at each station.		
OUT			
ca c10	2348 - Drum address.		
si 963	Selects "block in" from drum internal routine.		
ca c17	+150 - Number of registers being blocked in.		

bi 332	Address of first register in core memory to receive block in from drum.		
ca c11	2748-Drum address of first register in "block in" group.		
si 963	Selects "block in" internal routine.		
ca c18	+50-Number of registers being blocked in.		
bi 732	Address of first register in core memory to receive blocked in data.		
IN			
isp g25-1	Forms σ_a, σ_b, σ_f and σ_s for all station.		
OUT			
ca c19	+2498-Drum address of first register to be blocked in.		
si 963	Selects "block in" internal routine.		
ca c18	+50-Number of registers being blocked in.		
bi 482	Core address of first register receiving blocked in data.		
a0 976 cp p2-4	Forms counter to limit number of alteration cycles to 3(1 + number in 976).		
sp0	Stops computer after completion of 3 cycles		
IN			
ica c3	-1.0	-1.0	
its t3			-1.0

Note that the above counter was used for the test runs of this program. In any case the alteration procedure should be limited to prevent the possibility of the computer obtaining an unreasonable answer. As an example, should the web frame be to large the web flange can be reduced by predetermined amounts. However, large reductions could give a negative length of flange. A future programmer may want to change the value used

in the counter and therefore the number of cycles. However a counter must be used in all cases.

Now it becomes necessary to compare the values of the computed stresses with allowable values. To do this the computed values must be plus and a small program must be written to insure that all values are plus. Also, the maximum stress value at each point of equal scantlings must be determined. Remember that the web frame is symmetrical port and starboard, but the values of stress are not symmetrical. After determining the maximum value of stress at each station, the values are compared with allowable values and the scantlings altered.

ict pal		
p2, ica e5+c	$+(\sigma_f)$	σ_f(starboard side)
icp ml	If σ_f is minus perform sub-routine ml. If plus, do next instruction.	
its tl		$+\sigma_f$
ica e5+pb8+pb8	$+\sigma_f$	$+\sigma_f$(port side).
icp ml	Checks sign of σ_f.	
its t2		$+\sigma_f$
isu tl	$-\sigma_f$(starboard)	σ_f(port) - σ_f(starboard)
icp m2	Checks sign of σ_f(port) - σ_f(starboard) and if minus, goes to m2.	
ica t2	$+\sigma_f$	$+\sigma_f$
p3, isu c20	-(+20,000)	σ_f -(+20,000)(Lower value of stress limit).
icp m3	If (σ_f-20,000) is minus, go to m3 to reduce scantling values.	

isu c21	-8000	(σ_f-20.000)-8000 (8000 /in^2 is the range of stresses).	
icp p4	If value is minus, perform sub-routine p4 which moves forward to the next station.		
ica b3+c	+w_f	+w_f	
iad c1	+.5	w_f+.5 (Increases flange width).	
its b3+c			w_f+.5
ics c3	-(-1.0)	+1.0	
its t3			+1.0
p4, OUT			
ca p2+3	ica e5+pb8+pb8	ica e5+pb8+pb8	
su c7	-2	ica e5+pb8+pb8-2	
ts p2+3			ica e5+pb8+pb8-2
IN			
ict p2			
ica t3	-1.0	-1.0	
icp p6			
OUT			
ca c19	+2498-Drum address register.		
si 967	Selects drum block out procedure.		
ca c18	+50-Number of registers being blocked out.		
bo 482	Core memory address of first register of group being blocked out.		
ca c8	+2048-Drum address register of first number in a group being blocked in.		
si 963	Selects drum block in procedure.		
ca c12	800-Number of registers being blocked in.		

ca c12	+800	+800	
ad c17	+150	+950	
ad c2	+30	+980	
ts t8			+980
ca t8	+980		
si 963	Selects drum block in procedure.		
ca c12	+800		
bi 980			

The two block in procedures put numbers and instructions back into the core memory in preparation for another cycle of stress calculations of the altered scantlings. The block out instruction prior to the block in instructions puts new values of web flange width into the columns of numbers on the drum. The first block in instruction moves numbers into the core memory. The second block in instruction came as a result of "debugging" operations when it was determined necessary to replace all the addresses in the instructions back to their starting value involving the port side it was necessary for the programmer to write instructions that would decrease the addresses of the registers containing the starboard side values. In other words it was necessary to move up a column of numbers in the core memory. At the beginning of the second cycle

the instruction addresses were in error by a number equal to the number of cycles in that particular sub-routine. By blocking in the original instructions which remain on the drum into their assigned positions all the addresses were reset to their original value.

For cycles within a basic cycle of operations it is necessary to write a reset routine that returns the addresses back to their original values at the end of each inner cycle.

IN

isp g4	Starts cycle at g4.
isp pl+11	These two instructions skip the block out procedure in the main cycle. Since the block out has occured during the first cycle, the values remain in the drum and need not be blocked out again.

p6, i STOP

The following sub-routines are used in conjunction with the comparison and alteration sequence.

m1, ita m1+2			
imr c3	x-1.0	$(-1.0x-\sigma_f) = +\sigma_f$ (Makes σ_f plus).	
isp			
m2, ica t1	$+\sigma_f$	$+\sigma_f$(starboard)	
isp p3			
m3, ica b3+c	$+w_f$	$+w_f$	
isu c1	-.5	$w_f-.5$	
its b3+c			$w_f-.5$
isp p3+7			
c19,	+2498-Drum address.		
c20,	+20,000.0-Lower limit of allowable stress value.		
c21,	+8,000.0-Range of allowable stress values.		

Note that for this problem a very wide range of values was used to prevent the possibility of the computer seeking an impossible solution. If the stress change caused by the flange alteration were to be larger than the stress range, then a solution would be impossible with this program.

976 -2

i START AT p1

In programming it is necessary to use various constants to change units, to form equations and to change generated values by arithmetic

manipulations. These constants must be assigned registers or flads to be of use in the program. The constants listed below were assigned flad cl, c2, etc., the c being useful in remembering the nature of the input.

Tape fc 359-217-101
(24,6)

c1,	+0.0	
c2,	+30.0	A constant used to form the width of shell plating which is considered to be effective in forming the web beam.
c3,	-1.0	A constant useful in changing the sign of a value in the MRA.
c4,	+1.5	Used in calculation of the moment of inertia.
c5,	+64.0	Weight of a cubic foot of sea water in lbs/ft^2.
c6,	+0.0	Used to clear registers where the value in the register must be zero.
c7,	+2	Whirlwind number used in changing addresses in the interpreted mode.
c8,	+2048	A Whirlwind number used to assign addresses on the auxiliary drum.
c9,	2850	
c10,	+2348	
c11,	+2748	
c12,	+800	Number of registers in a blockout procedure.
c13,	+216	
c14,	+1	Whirlwind number used in changing addresses.
c15,	+12.0	Converts feet or inches to inches or feet.
c16,	+0.707	$1/\ 2 = \sin 45^\circ$ or $\cos 45^\circ$.
c17,	+150	Number of registers in block out procedures.
c18,	+50	
t1, through t8,		+0.0 - Temporary registers for calculations.

The following preset parameters are part of the inputs that do not vary with vessel type. Note that each preset parameter listed below is generated from the present parameters in the variable input tape.

pb1 = pa1-1	Number of segments in the half girth of a web frame.
pb2 = pa1-2	Two less than the number of stations on a half girth. Used in moment formation.
pb3 = pa2-1	Number of segments between the origin and deck edge.
pb4 = pa3 +pa3 -2	Number of registers from the origin register to the bottom of the starboard stanchion.

Also contained in Tape 359-217-101 are the storage assignments for generated numbers.

132 | a1, +0.0 DITTO 48 +0.0	Sine of the angle storage. Note that this instruction puts zeros in 25 double length registers.
182 | a2, +0.0 DITTO 48 +0.0	Cosine storage.
232 | a5, +0.0 DITTO 48 +0.0	Girth segment lengths storage
532 | e4, +0.0 DITTO 48 +0.0	Storage for vertical water loads.
582 | e3, +0.0 DITTO 48 +0.0	Storage for horizontal water loads.
832 | d3, +0.0 DITTO 48 +0.0	Storage for the inverse of the moment of inertia $1/I_{N.A.}$

```
882| d2, +0.0
    DITTO
    48   +0.0

732| dl, +0.0
    DITTO
    48   +0.0

782| sl,                Library sub-routine for finding square roots.
```

The remainder of tape 359-217-101 consists of the various sub-routines that perform the functions listed in the flow diagram, Figure V. A discussion of each sub-routine is placed at the beginning of the list of instructions that comprise the sub-routine.

The form of presentation of the following sub-routines was found to be an aid in the organization and understanding of the problem. Since continuity of thought is so important to the writing of a workable program, the increased effort in writing the flow of information into the MRA, accumulation of data in the MRA and the values transferred from the MRA was considered worthwhile. Other methods of organizing material could have been used; however, the authors found that this method was both effective and presented the ideas in a convenient form.

The following sub-routine forms the sin θ and cos θ of the frame segments by the use of the basic equations listed below.

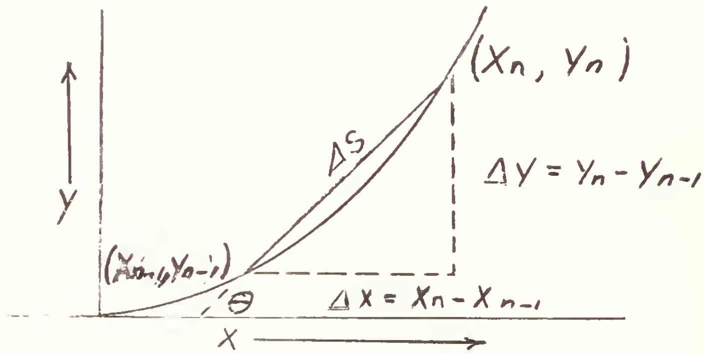
$$\Delta s_n = \Delta x_n^2 + \Delta y_n^2$$

$$\Delta x_n = x_n - x_{n-1}$$

$$\Delta y_n = y_n - y_{n-1}$$

$$\sin\theta = \Delta y/\Delta s$$

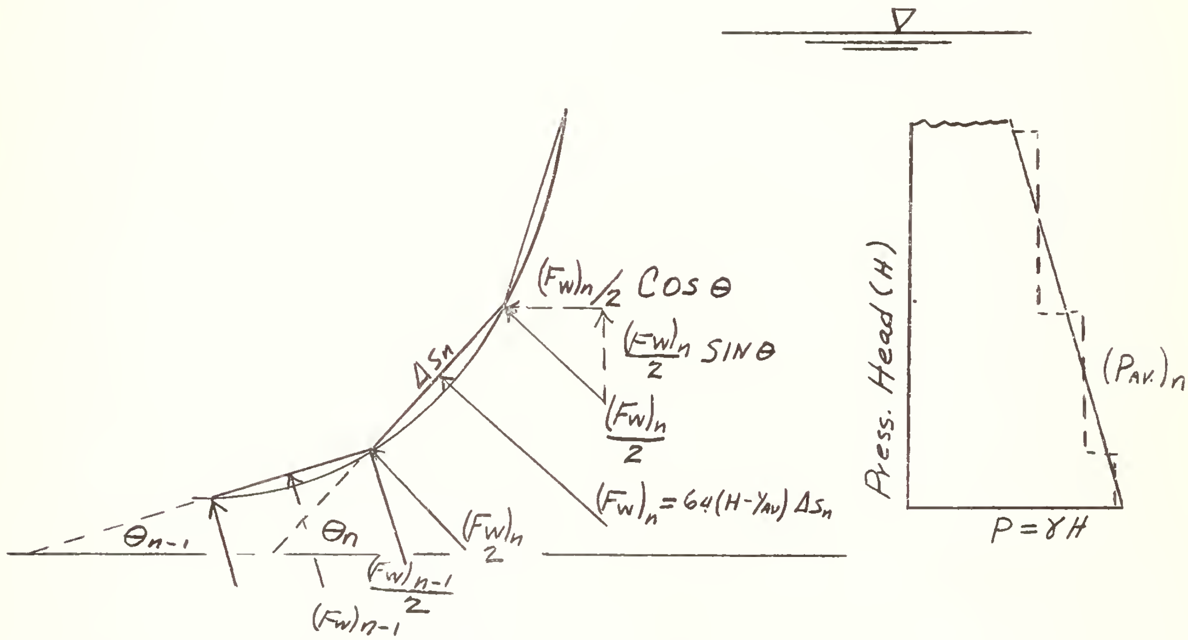
$$\cos\theta = \Delta x/\Delta s$$



Instruction	Input to MRA	In MRA	Transfer from MRA
gl, ita gl+21	This instruction transfers the address in the control element to the address of the instruction in gl+21 and adds one. (See glossary of instructions).		
icr pbl	Sets the cycle count to the number of segments on the side of the frame. This routine will be performed pbl times		
ica xl+2+c	$+x_n$	$+x_n$	
isu xl+c	$-x_{n-1}$	$x_n - x_{n-1}$	
its t1			Δx_n
imr t1	$\times \Delta x_n$	Δx_n^2	
its t2			Δx_n^2

Instruction	Input to MRA	In MRA	Transfer from MRA
	(continued)		
ica yl+2+c	$+y_n$	$+y_n$	
isu yl+c	$-y_{n-1}$	$+y_n-y_{n-1}$	
its t3			Δy_n
imr t3	Δy_n	Δy_n^2	
iad t2	$+\Delta x_n^2$	$\Delta y_n^2 + \Delta x_n^2$	
SP sl	sl is a sub-routine that extracts the square root of the number in the MRA and returns the square root of the number back into MRA.		
its a5+c			$\Delta s = \sqrt{\Delta x^2 + \Delta y^2}$
ica tl	$+\Delta x_n$	$+\Delta x_n$	
idv a5+c	$\div \Delta x_n$	$\Delta x_n/\Delta s_n$	
its a2+2+c			$(\cos \theta)_n = \Delta x_n/\Delta s_n$
ica t3	$+\Delta y_n$	Δy_n	
idv a5+c	$\div \Delta s_n$	$\Delta y_n/\Delta s_n$	
its al+2+c			$(\sin \theta)_n = \Delta y_n/\Delta s_n$
ict gl+2	Puts gl+2 in the control element and starts the cycle over again.		
isp	Address put into this instruction by the ita instruction in flad gl.		

The sub-routine that follows forms the water loads from the origin to the main deck. In this sub-routine the water loads are assumed to be uniformly distributed along the shell segment and the center of pressure is assumed to act at the mid-point of the segment. After formation of the total load on the segment, the load is divided by 2 and half of the load is placed at each end of the segment. The approximation of a continuous beam under a trapezoidal shaped pressure load by a uniform load is only valid when the shell segments are small in size. As the loads are formed, the program converts the loads into horizontal and vertical components.



Instruction			Input to MRA	In MRA	Transfer from MRA
ita	g2+18	(See glossary of instructions).			
icr	pb3	Sets cycle counter for number of segments in the starboard side from origin to deck edge.			
g2,	ics	yl+c	$-y_n$	$-y_n$	
	isu	yl+2+c	$-y_{n+1}$	$-y_{n+1}-y_n = -(y_{n+1}+y_n)$	

Instruction	Input to MRA	In MRA	Transfer from MRA
	(continued)		
imr c1	0.5	$-(y_{n+1}+y_n)/2 = -y_{av}$	
iad e2	+H(water head)(ft)	$H-y_{av}$	
imr c5	$\times 64$ /ft^3	$64(H-y_{av})$	
imr a5+c	$\times \Delta s$ (ft)	$64\Delta s(H-y_{av}) = F_w$	
imr c1	$\times 0.5$	$F_w/2$ (assumes simple support)	
its t1			$F_w/2$
imr a2+2+c	$\times(\cos\theta)_{n+1}$	$(\cos\theta)_{n+1}F_w/2 = (V_w)_{n+1}$	
its e4+2+c			$(V_w)_{n+1}$
iad e4+c	$V_{w_{n-1}}$	$V_{w_{n-1}}+V_n = V_w$	
its e4+c			$(V_w)_n$
ica t1	$+(F_w)/_2^n$	$+(F_w/2)_n$	
imr a1+2+c	$+(\sin\theta)_n$	$(\frac{F_w}{2}\sin\theta)_n = (H_w)_n$	
its e3+2+c			$(H_w)_n$
iad e3+c	$(H_w)_{n-1}$	$(H_w)_{n-1}+(H_w)_n = H_{w_n}$	
its e3+c			$(H_w)_n$
ict g2	cycle back to g2.		
isp	Address provided by ita instruction.		

Formation of vertical forces is accomplished by the programs listed below. Vertical forces are the algebraic addition of buoyant forces which act in the upward direction and the weight forces which act downward. Upward forces are taken as positive. Note that a separate program is required for each side. The V_w forces are symmetrical and can be stored in 50 registers. The weight forces are non-symmetrical and the weight for each of the stations must be stored. In the program for forming the starboard vertical forces, the addresses of the V_w moves down a column of registers of increasing addresses which is the manner of operation of the e4+c address. To move the other direction up a column of numbers a small Whirlwind program is required to reduce the addresses by 2 for each cycle.

Instruction	Input to MRA	In MRA	Transfer from MRA
ita (See glossary of instructions).			
icr pa2			
gl0, ica e4+c	$+V_w$	$+V_w$	
iad e5+c	$-W_t$	$+V_w - W_t = V_t$	
its e5+c			V_t
	End of starboard side program.		
ica e4+c	$+V_w$	$+V_w$	
iad e5+pb8+pb8	$-W_t$	$+V_w - W_t = V_t$	
its e5+pb8+pb8			V_t
	Goes out into Whirlwind to change addresses of weight loads.		
OUT			

Instruction	Input to MRA	In MRA	Transfer from MRA
	(continued)		
ca g10+4	iad e5+pb8+pb8	iad e5+pb8+pb8	
su c7	-2	iad e5+pb8+pb8-2	
ts g10+4			iad e5+pb8+pb8-2
td g10+5			e5+pb8+pb8-2
IN			
ict g10+2			
isp			

After forming sin θ and cos θ of each of the segments, it was necessary to find the sin and cos of the angle ϕ formed by the tangent to the curve at each station and the horizontal axis. cos ϕ and sin ϕ were determined by averaging the cosines and sines of the angles of the chords on either side of the station. While it was considered to be more accurate to find the tan ϕ or the slope of the curve at each station, the possibility of tan $\phi = \Delta y/\Delta x$ becoming infinity rendered this impossible. Further, only sin ϕ and cos ϕ were necessary for the purposes of the program and tan ϕ would have required additional storage and programming. This implies two conditions that do not exist. One, the rate of change of angles should be equal and secondly, the

$$\sin \frac{(\theta_1 + \theta_2)}{2}$$

does not equal

$$\frac{\sin \theta_1 + \sin \theta_2}{2}$$

and

$$\cos \frac{(\theta_1 + \theta_2)}{2}$$

does not equal

$$\frac{\cos \theta_1 + \cos \theta_2}{2}.$$

However, the resulting error will be small as long as the station points are judiciously selected to maintain small nearly equal angle changes. Should more accurate angles be necessary the programmer could utilize trigonometric identities and equal angle changes.

An additional problem in this sub-routine was to insure that the centerline values of angles on deck and bottom represented 0° and 180° respectively. As was mentioned earlier the sin and cos of 135° were placed at the corner station.

Instruction	Input to MRA	In MRA	Transfer from MRA
g3, ita g3+20	(See glossary of terms).		
icr pb2			
ica a1+2+c	$+\sin \theta_1$	$+\sin \theta_1$	
iad a1+4+c	$+\sin \theta_2$	$+\sin \theta_1 + \sin \theta_2$	
imr c1	$\times 0.5$	$\frac{\sin \theta_1 + \sin \theta_2}{2} = \sin \phi$	
its a1+2+c			$\sin \phi$
ica a2+2+c	$+\cos \theta_1$	$+\cos \theta_1$	
iad a2+4+c	$+\cos \theta_2$	$\cos \theta_4 + \cos \theta_2$	

Instruction	Input to MRA	In MRA	Transfer from MRA

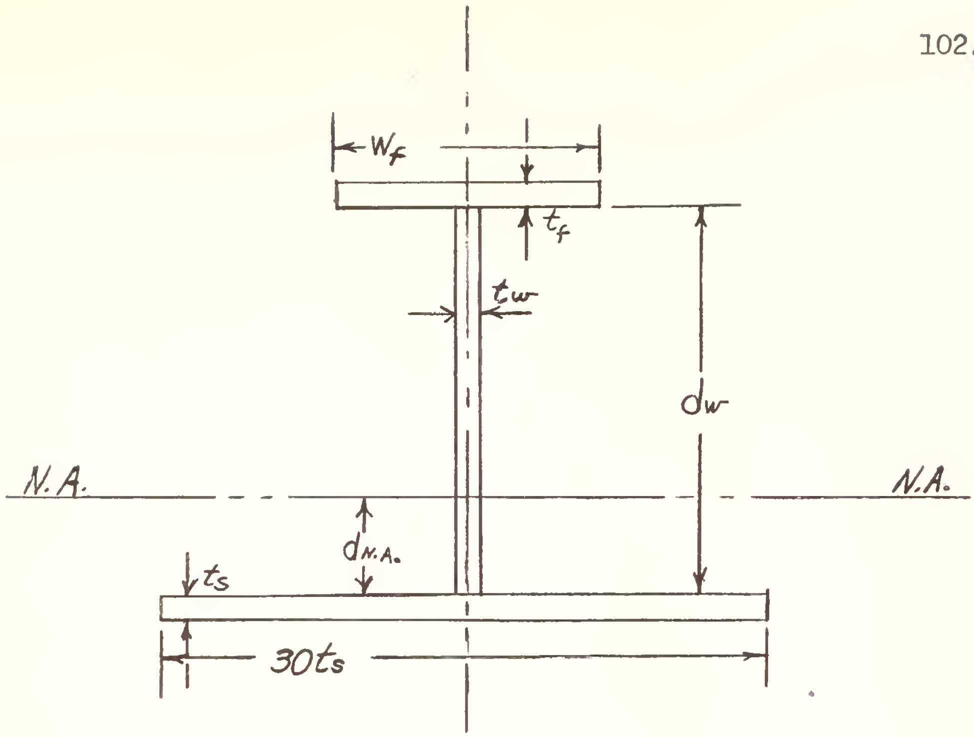
(continued)

imr c1	0.5	$\frac{\cos\theta_1 + \cos\theta_2}{2} = \cos\phi$	
its a2+2+c			$\cos\phi$
ict g3+2			

The following orders sets 0° and 180° in the center line deck and keel and, also sets 135° in the corner angle.

ica c6	+0.0	+0.0	
its a1			+0.0
its a1+pb1+pb1			+0.0
ics c3	+1.0	+1.0	
its a2			+1.0
ica c3	-1.0	-1.0	
its a2+pb1+pb1			-1.0
ica c16	+0.707	+0.707	
its a1+pb3+pb3			+0.707
ics c16	-0.707	-0.707	
its a2+pb3+pb3			-0.707
isp			

Since web frames are built up sections it is necessary to compute the moment of inertia at each station around the girth. The width of shell plating assumed to be effective in forming the web beam is thirty times the plate thickness.



The following sub-routine uses the relationships below in forming the area, moment of inertia and distance to the neutral axis of the web from the shell.

$$A_f = w_f t_f \qquad m_f = (d_w + \frac{t_f}{2})A_f \qquad I_f = (d_w + \frac{t_f}{2})m_f$$

$$A_w = d_w t_w \qquad m_w = \frac{d_w}{2} A_w \qquad I_w = \frac{d_w}{1.5} m_w = \frac{t_w d_w}{3}$$

$$A_s = 30\ t_s^2 \qquad m_s = \frac{t_s}{2} A_s \qquad I_s = \frac{t_s}{1.5} m_s$$

$$A_t = A_f + A_w + A_s \qquad m_t = m_f + m_w + m_s \qquad I_t = I_f + I_w + I_s$$

$$d_{NA} = \frac{m_t}{A_t} \qquad I_{NA} = I_t - A_t d_{NA}^2$$

Instruction	Input to MRA	In MRA	Transfer from MRA
g4, ita g5+24			
icr pal			
ica b1+c	$+d_w$	$+d_w$	
imr b2+c	t_w	$d_w \times t_w = A_w$	
its t1			A_w
imr b1+c	$\times d_w$	$A_w \times d_w$	
imr c1	$\times +0.5$	$0.5 \times A_w \times d_w = m_w$	
its t2			m_w
ica b4+c	$+t_f$	$+t_f$	
imr b3+c	$\times w_f$	$t_f \times w_f = A_f$	
its t3			A_f
ica b4+c	$+t_f$	$+t_f$	
imr c1	$\times 0.5$	$0.5 \times t_f$	
iad b1+c	$+d_w$	$d_w + t_f/2$	
imr t3	$\times A_f$	$A_f(d_w + t_f/2) = m_f$	
its t4			m_f
ica b5+c	$+t_s$	$+t_s$	
imr b5+c	$\times t_s$	$(t_s)^2$	
imr c2	$\times 30$	$30(t_s)^2 = A_s$	
its t5			A_s

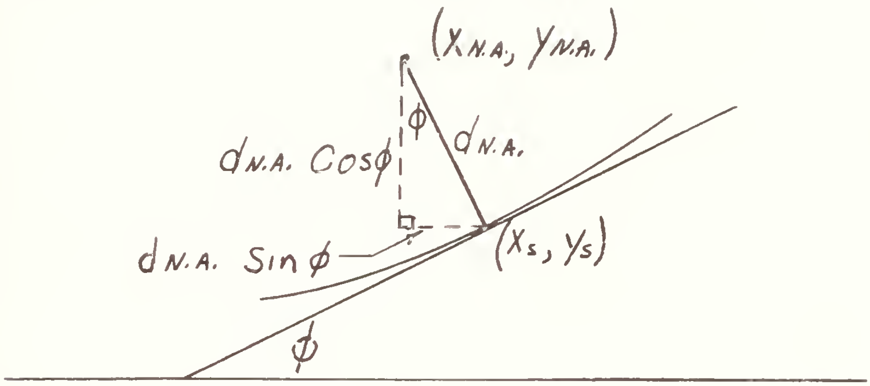
(continued)

Instruction	Input to MRA	In MRA	Transfer from MRA
imr b5+c	$\times t_s$	$A_s \times t_s$	
imr c1	$\times .5$	$\frac{A_s t_s}{2} = m_s$	
its t6			m_s
ica t2	$+m_w$	m_w	
iad t4	$+m_f$	$m_w + m_f$	
isu t6	$-m_s$	$m_w + m_f - m_s = M_t$	
its t7			M_t
ica t1	$+A_w$	$+A_w$	
iad t3	$+A_f$	$A_w + A_f$	
iad t5	$+A_s$	$A_s + A_w + A_f = A_t$	
its d2+c			A_t
ica t7	$+M_t$	$+M_t$	
idv d2+c	$\div A$	$\frac{M_t}{A_t} = d_{N.A.}$	
its d1+c			$d_{N.A.}$
g5, ica t2	$+m_w$	$+m_w$	
imr b1+c	$\times d_w$	$m_w d_w = \frac{A_w d_w^2}{2}$	
idv c4	1.5	$\frac{A_w d_w^2}{3} = I_w$	
its t1			I_w

(continued)

Instruction	Input to MRA	In MRA	Transfer from MRA
ica b4+c	t_f	t_f	
imr c1	$\times 0.5$	$t_f/2$	
iad b1+c	d_w	$d_w+t_f/2$	
imr t4	$\times m_f$	$m_f(d_w+.5t_f) = A_f(d_w+t_f/2)^2$	I_f
iad t1	$+I_w$	I_w+I_f	
its t1			(I_f+I_w)
ica t6	$+m_s$	$+m_s$	
idv c4	$\div 1.5$	$\frac{m_s}{1.5} = \frac{w_s\ t_s^2}{3}$	
imr b5+c	$\times t_s$	$\frac{w_s t_s^3}{3} = I_s$	
iad t1	I_w+I_f	$I_w+I_f+I_s = I_{about\ shell}$	
its t1			I_{shell}
ics d2+c	$-A_t$	$-A_t$	
imr d1+c	$\times d_{N.A.}$	$-AI\ d_{N.A.}$	
imr d1+c	$\times d_{N.A.}$	$-AI\ d^2_{N.A.}$	
iad t1	$I_{about\ shell}$	$I_{N.A.} = I_{shell} - AI\ d^2_{N.A.}$	
its t1			$I_{N.A.}$
ics c3	$-(-1.0)$	$+1.0$	
idv t1	$\div I_{N.A.}$	$1/I_{N.A.}$	
Its d3+c			$1/I_{N.A.}$

When working with beams, all forces and moments are considered to act along the neutral axis. To make the program more general, the original coordinate inputs were the x and y coordinates of the inner surface of hull shell. The coordinates of the neutral axis may be formed by offsets from the shell coordinates. The reader will notice that such a program allows alteration of the web section as desired to produce the practical results. The offset distance is $d_{N.A.}$



$$x_{N.A.} = x_s - d_{N.A.} \sin \phi,$$

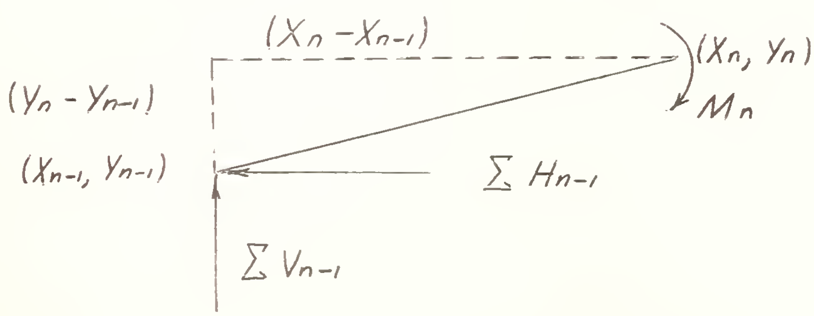
$$y_{N.A.} = y_s + d_{N.A.} \cos \phi.$$

The following program forms the coordinates of the neutral axis. Since this program is a continuation of the above sub-routine, the counter instructions are still in effect.

Instruction	Input to MRA	In MRA	Transfer from MRA
g6, ics dl+c	$+d_{N.A.}$	$-d_{N.A.}$ (inch)	
idv cl5	$\div 12$	$-d_{N.A.}/12$ (ft)	
its tl			$-d_{N.A.}/12$

Instruction	Input to MRA	In MRA	Transfer from MRA
	(continued)		
imr a1+c	$x \sin \phi_{shell}$	$-\dfrac{d_{N.A.} \sin \phi}{12}$	
iad x1+c	$+x_{shell}$	$x_s - \dfrac{d_{N.A.} \sin \phi}{12} = x_{N.A.}$	
its x1+c			$x_{N.A.}$
ics t1	$-(-d_{N.A.}/12$	$+d_{N.A.}/12$	
imr a2+c	$x \cos \phi_{shell}$	$\dfrac{d_{N.A.}}{12} \cos \phi$	
iad y1+c	y_{shell}	$y_s + \dfrac{d_{N.A.}}{12} \cos \phi = y_{N.A.}$	
its y1+c			$y_{N.A.}$
ict g4			
isp			

The moments at each station are formed by multiplying the summation of the horizontal and vertical components of the loads by the vertical and horizontal projections of the segment.



$$-\sum V_{n-1}(x_n - x_{n-1}) - \sum H_{n-1}(y_n - y_{n-1}) + m_n = 0$$

The following sub-routine forms the moments at each station due to the weight and water pressure loads on the starboard side. Note that the first few instructions put +0.0 into t1, t2, t3. This was necessary due to their use in forming the summations. In addition when using this sub-routine to form m_n, t4 and b3 must be set to zero. When using this to compute the bending moment after solving for the redundant, the value of the redundant m_0 must be put into t4 and m_o/I_0 in b3.

Instruction	Input to MRA	In MRA	Transfer from MRA
g7, ita g8+35			
icr pb1			
ica c6	+0.0	+0.0	
its t1			+0.0
its t2			+0.0
its t3			+0.0
ica e5+c	$+V_{n-1}$	V_{n-1}	
iad t1	$+\sum^{n-2} V$	$\sum^{n-1} V$	
its t1			$\sum^{n-1} V$
ics x1+2+c	$-(x_{na})_n$	$(-x_{na})_n$	
imr t1	$\times \sum^{n-1} V$	$\Delta x \sum^{n-1} V$	$= (m_n)_v$

Instruction	Input to MRA	In MRA	Transfer from MRA
	(continued)		
its t3			(m_n)
ica e3+c	$+H_w$	$+H_w$	
iad t2	$\sum^{n-2} H_w$	$\sum^{n-1} H_w$	
its t2			$\sum^{n-1} H_w$
ics y+2+c	$(-y_{N.A.})_N$	$(-y_{N.A.})_N$	
iad y1+c	$(+y_{N.A.})_{n-1}$	$-\left[(y_{N.A.})_N - (y_{N.A.})_{n-1}\right] = \Delta_y$	
imr t2	$\times \sum^{n-1} H_w$	$\Delta_y \sum^{n-1} H_w$	
iad t3	$(m_n)_{n-1}$	$(m_n)_n$	
iad t4	$\sum^{n-1} (m_n)$	(m_n)	
its t4			(m_n)
imr d3+2+c	$\times\ 1/I$	m_n/I	
its b3+2+c			m_n/I
ict g7+8			

The following section of the sub-routine forms moments port side. Remember that the coordinates of neutral axis and the horizontal loads are stored for one side. The sub-routine must move up the stored column of numbers to form the moments.

Instruction	Input to MRA	In MRA	Transfer from MRA
icr pal			
g8, ica e5+pal+pal+c	$+V_n$	$+V_n$	
iad t1	$\sum^{n-2} V$	$\sum^{n-1} V+V_n = \sum^{n-1} V$	
its t1			$\sum^{n-1} V$
ica x1+pb2+pb2	$+x_{n+1}$	$+x_{n+1}$	
isu x1+pb1+pb1	$-x_n$	$x_{n+1}-x_n = \Delta_x$	
imr t1	$\sum^{n-1} V$	$\Delta_x \sum^{n-1} V = m_n$	
its t3			(m_n)
ica e3+pb1+pb1	$+H_{n-1}$	$+H_{n-1}$	
iad t2	$\sum^{n-2} H_{n-2}$	$\sum^{n-2} H_{n-2}+H_{n-1} = \sum^{n-1} H_n$	

Instruction	Input to MRA	In MRA	Transfer from MRA
	(continued)		
its t2			$\sum^{n-1} H_n$
ica y1+pb2+pb2	$(+y_{N.A.})_{n+1}$	$(+y_{N.A.})_{n+1}$	
isu y1+pb1+pb1	$(-y_{N.A.})$	$\left[(y_{N.A.})_{n+1} - (y_{N.A.})_n\right]$	
imr t2	$\sum^{n-1} H_1$	$\Delta_y \sum^{n-1} H = (m_n)_H$	
iad t3	$(+m_n)_v$	$(m_n)_v + (m_n)_H = m_n$	
iad m1+pb1+pb1+c	$\sum^{n-1} m_n$	$\sum^{n-1} m + m_n = \sum^{n} m$	
imr d3+pb1+pb1	1/I	$\sum^{n} m/I$	
OUT	The program now goes out into Whirlwind to change the addresses for each cycle.		
ca g8+3	ica x1+pb2+pb2	ica x1+pb2+pb2	
td g8+4	Puts the address of g8+3 into the address of g8+4 now reads isu x1+pb2+pb2.		
su c7	-(+2W.W.)	ica x1+pb2+pb2-2	
ts g8+3			ica x1+pb2+pb2-2
ca g8+7	ica e3+pb1+pb1	ica e3+pb1+pb1	

Instruction	Input to MRA	In MRA	Transfer from MRA
	(continued)		
su c7	-(+2 W.W.)	ica e3+pb1+pb1-2	
ts g8+7			ica e3+pb1+pb1-2
ca g8+10	ica y1+pb2+pb2	ica y1+pb2+pb2	
td g8+11	(Instruction in g8+11 is now isu y1+pb2+pb2).		
su c7	-(+2 W.W.)	ica y1+pb2+pb2-2	
ts g8+10			ica y1+pb2+pb2-2
ca g8+15	+imr d3+pb1+pb1	+imr d3+pb1+pb1	
su c7	-(+2 W.W.)	+imr d3+pb1+pb1-2	
ts g8+15			imr d3+pb1+pb1-2
IN			
ict g8			
isp			

Since all moments due to applied loads and forces had been formed, it was possible to perform the integrations of moments to obtain the slopes and deflections previously discussed in the procedure. At this point in the programming the redundants m_0, p_0, and q_0 must be considered. m_0 will appear as a constant value of moment at each station throughout the girth. The moments due to p_0 and q_0 depend upon the value of y and x at each station. Since the web frame was assumed to

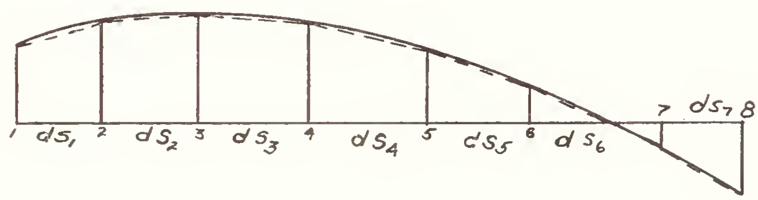
$$m_{redundant} = p_0 y_n + q_0 x_n + m_0$$

be symmetrical; the slope changes and deflections around the entire girth caused by the redundants will be double the slopes and deflections on one side. For convenience in integration, the redundants will be integrated around the starboard side.

The method of integration used was the trapezoidal rule which implies linear slope of the moment curve between stations on the moment curve. The area under the curve

$$= \sum_{n=1}^{7} \left[\left(\frac{M}{I}\right)_n + \left(\frac{M}{I}\right)_{n+1} \right] \frac{ds_n}{2}$$

$$A = \left[\left(\frac{M}{I}\right)_1 + \left(\frac{M}{I}\right)_2 \frac{ds}{2} + \left(\frac{M}{I}\right)_2 + \left(\frac{M}{I}\right)_3 \right] \frac{ds_2}{2} + \ldots$$



As can be seen from the figure, the trapezoidal rule will cause small error providing the curve is smooth and stations are closely spaced. Despite the small error, the above method of integration was chosen because it is readily applicable to computer programming and because random station spacing was necessary to approximate a curved figure by a series of straight lines.

In the process of "debugging" the program several improvements in the sequence of operations for the formation of the integrals were made. The results of these improvements and errors in addresses of the initial program for the integration procedures alters the procedure as written. The techniques used and explained in the following pages are correct.

The major improvement was the inclusion of the integration routines under one sub-routine. All the integrals for m_0, p_0, q_0 and m_n/I were performed under one cycle counter. Each of the stanchion redundant forces R and S were under a separate cycle. The routine

$$p_0 \int \frac{y}{I}\, ds$$

was not performed. To obtain the coefficient of p_0, the coefficient of m_0 which is

$$\int \frac{y}{I}\, ds$$

was used. The group of instructions included under flad g9 were added to insure that zeros were initially placed in the registers that were to hold the matrix. Also, the addresses for forming the port side integrals were found to be in error by two registers.

The instructions listed below are correct and replace the integration routines listed under flads g11 through g22 of the detailed description. Unfortunately, these alterations were not made in sufficient time to allow the correction of the detailed explanation. These instructions should be read from left to right.

```
g9, ita g22
ict g2+2
imr a5+c
imr x1+c
imr x1+2+c
iad d1+24
its t1
iad t1
g14, ica t1
imr y1+2+c
its d1+12
imr c1
imr b3+c
iad t3
its d1+52
ica x1+2+c
imr c1
iad b3+pa1+pa1+c
its d1+50
icay1+pb2+pb2
imr c1
imrb3+pb1+pb1+c
iad t1
its d1+54
ts g18+2
ts g19
ts g19+10
ict g11
icax1+pb4+c
imr c1
its d1+56
imra5+pb4+c
iad d1+56
its t1
icr 30
icr pb1
iad d1
imr d3+c
imr d3+2+c
its d1+24
ica y1+2+c
imr a5+c
imr y1+c
iad t1
g15, ica b3+c
iad d1+50
its t3
imr a5+c
g17, ica x1+c
imr b3+2+c
iad d1+54
imr a5+pb2+pb2
g19,icay1+pb1+pb1
imrb3+pa1+pa1+c
iad d1+52
its t1
imra5+pb2+pb2
OUT
ts g19+6
su c7
su c7
ica d1+2
isu x1+pb4
its t1
icax1+pb4+2+c
imr c1
its d1+56
imry1+pb4+c
ica c6
g11, ica d3+c
its d1
its t1
iad t1
g13, ica y1+c
imr d3+2+c
iad d1+2
its t1
imr a5+c
iad b3+2+c
its d1+50
ica y1+2+c
imr c1
imr b3+c
iad t3
its d1+54
imr c1
imrb3+pb1+pb1+c
iad t1
its d1+52
icsx1+pb2+pb2
imr c1
ca g18+2
ts g19+16
ts g19+3
ts g19+13
its d1+10
its t3
imrb3+pb4+c
isux1+pb4
its t2
ica t1
iad d1+16
its d1+c
iad d3+2+c
g12, icax1+c
ica x1+2+c
imr a5+c
imr d3+c
its t2
its d1+2
ica t2
iad d1+12
imr a5+c
g16, ica y1+c
imr b3+2+c
iad d1+52
its t3
imr a5+c
g18,icab3+pb1+pb1+c
iad d1+50
its t1
imra5+pb2+pb2
icsx1+pb1+pb1
imrb3+pa1+pa1+c
iad d1+54
su  c7
ca g19+3
ca g19+13
IN
g20,icr pa5
imra5+pb4+c
iad d1+56
its t4
imrb3+pb4+2+c
imrd3+pb4+c
its d1+16
```

```
ica  t2
iad dl+16
iad dl+26
iad dl+26
iad dl+36
iad dl+36
iad dl+6
its dl+30
its dl+34
its t3
imrb3+pb6+pb6
isuxl+pb5
its t2
OUT
ts g21+16
its tl
ica t2
iad dl+18
iad dl+28
iad dl+28
iad dl+48
iad dl+48
iad dl+8
its dl+40
its dl+44
imrd3+pb4+2+c
its dl+16
its dl+26
its dl+26
its dl+36
its dl+36
its dl+6
ica dl+16
g21, icr pa6
imra5+pb5+c
iad dl+58
its t4
imrb3+pb6+pb6-2
ca g21+16
IN
imryl+pb5+c
imrd3+pb5+2+c
its dl+18
its dl+28
its dl+28
its dl+48
its dl+48
its dl+8
ica dl+18
g22, isp0
its t2
ica tl
ica t2
ica t3
ica t4
ica tl
ict g20+1
its dl+32
icaxl+pb5+c
imr cl
its dl+58
imra5+pb5+c
iad dl+58
ts g21+7
ica tl
iad dl+18
its t2
ics tl
ics t2
ica t3
ica t4
ica tl
ict g21+1
itx dl+42
imryl+pb4+2+c
imrxl+pb4+c
imrxl+pb4+2+c
imr tl
imr t2
iad t2
ica dl+6
ica dl+26
isuxl+pb5
its tl
icaxl+pb5+2+c
imr cl
its dl+58
su c7
imrd3+pb5+c
its dl+18
imryl+pb5+2+c
imrxl+pb5+c
imrxl+pb5+2+c
imr tl
imr t2
iad t2
ica dl+8
ica dl+28
```

The results of each integration are stored to form the matrix as shown by Fig. VI. The following sub-routine performs the integration of the change of slope around the girth of the web frame due to redundant moment m_0.

$$\Delta\theta = \int_0^0 \frac{m_0}{I}\, ds = 2\int_0^A \frac{m_0}{I}\, ds = 2m_0 \int_0^A \left(\frac{1}{I_n} + \frac{1}{I_{n+1}}\right)\frac{ds_n}{2} = m_0 \int_0^A \left(\frac{1}{I_n} + \frac{1}{I_{n+1}}\right) ds_n$$

Instruction	Input to MRA	In MRA	Transfer from MRA
gl1, ita gl5+9	(See glossary of instructions).		
icr pbl	(Sets cycle counter equal to the number of stations on a side minus 1).		
ica d3+c	$+1/I_{n-1}$	$+1/I_{n-1}$	
iad d3+2+c	$+1/I_n$	$+1/I_n + 1/I_{n-1}$	
imr a5+c	$\times ds_n$	$(1/I_n + 1/I_{n-1})ds_n$	
iad d1	$+\sum^{n-1}(1/I_n + 1/I_{n-1})ds_{n-1}$	$\sum^{n}(1/I_n + 1/I_{n-1})ds_n$	
its d1			$\sum^{n}(1/I_n + 1/I_{n-1})ds_n$

The instructions below find the deflection in the y-direction due to the moment caused by the shear redundant q_0.

$$\Delta y = \int_0^0 x(q_0 x)ds = 2\int_0^A x(q_0 x)ds = 2q_0 \sum_1^{n-1}\left[\frac{(x_{n-1})^2}{I_{n-1}} + \frac{(x_n)^2}{I_n}\right]\frac{ds}{2}$$

Instruction	Input to MRA	In MRA	Transfer from MRA
gl2, ica xl+c	$+x_{n-1}$	$+x_{n-1}$	
imr xl+c	$\times x_{n-1}$	$(x_{n-1})^2$	
imr d3+c	$\times 1/I_{n-1}$	$(x_{n-1})^2/I_{n-1}$	
its tl			$(x_{n-1})^2/I_{n-1}$
ica xl+2+c	$+x_n$	x_n	
imr xl+2+c	$\times x_n$	x_n^2	
imr d3+2+c	$\times 1/I_n$	$(x_n)^2/I_n$	
iad tl	$+(x_{n-1})^2/I_{n-1}$	$(x_n)^2/I_n + (x_{n-1})^2/I_{n-1}$	
imr a5+c	$\times ds_n$	$(x_n)^2/I_n + (x_{n-1})^2/I_{n-1}\ ds_n$	
iad dl+24	$+\sum^{n-1} ds_{n-1}\ (x_n/I_n)^2 + (x_{n-1})^2/I_{n-1}$	$\sum^{n} (x_n)^2/I_n + (x_{n-1})^2/I_{n-1}\ ds_n$	
its dl+24			$\sum^{n} (x_n)^2/I_n + (x_{n-1})^2/I_{n-1}\ ds_n$

The deflection in the x-direction due to m_0 was found by performing the integration

$$\Delta x = \int_0^0 y \frac{m_0}{I}\, ds = 2\int_0^A y \frac{m_0}{I}\, ds = 2m_0 \sum_1^{n-1} \left[(y_{n-1}/I_{n-1}) + (y_n/I_n) \right] \frac{ds_n}{2} .$$

The instructions starting with gl3, perform this integration.

Instruction	Input to MRA	In MRA	Transfer from MRA
gl3, ica yl+c	$+y_{n-1}$	$+y_{n-1}$	
imr d3+c	$\times\ 1/I_{n-1}$	y_{n-1}/I_{n-1}	
its tl			y_{n-1}/I_{n-1}
ica yl+2+c	$+y_n$	$+y_n$	
imr d3+2+c	$\times\ 1/I_n$	y_n/I_n	
iad tl	$+\ y_{n-1}/I_{n-1}$	$(y_n/I_n+y_{n-1}/I_{n-1})$	
imr a5+c	$\times\ ds_n$	$(y_n/I_n+y_{n-1}/I_{n-1})ds_n$	
iad dl+2	$+\sum_1^{n-1}(y_n/I_n+y_{n-1}/I_{n-1})ds_{n-1}$	$\sum_1^{n}(y_n/I_n+y_{n-1}/y_{n-1})ds_n$	
its dl+2			$\sum_1^{n}(y_n/I_n+y_{n-1}/I_{n-1})ds_n$

The following section of the sub-routine performs the integration of the moment due to $p_0 = p_0 y$ around the girth.

$$\Delta\theta = \int_0^0 \frac{p_0 y}{I} ds = 2p_0 \int_0^A \frac{y}{I}\, ds = 2p_0 \sum \left(\frac{y_n}{I_n} + \frac{y_{n+1}}{I_{n+1}}\right)\frac{ds_n}{2}$$

Instruction	Input to MRA	In MRA	Transfer from MRA
gl4, ica yl+c	$+y_{n-1}$	$+y_{n-1}$	
imr d3+c	$\times 1/I_{n-1}$	y_{n-1}/I_{n-1}	
its t1			y_{n-1}/I_{n-1}
ica yl+2+c	$+y_n$	$+y_n$	
imr d3+2+c	$\times 1/I_n$	y_n/I_n	
its t2			y_n/I_n
iad t1	$+y_{n-1}/I_{n-1}$	$y_n/I_n+y_{n-1}/I_{n-1}$	
imr a5+c	$\times ds_n$	$(y_n/I_n+y_{n-1}/I_{n-1})ds_n$	
iad dl+10	$\sum^{n-1}(y_{n-1}/I_{n-1}+y_{n-2}/I_{n-2})ds_{n-1}$	$\sum^{n}(y_n/I_n+y_{n-1}/I_{n-1})ds_n$	
its dl+10		$\sum^{n}(y_n/I_n+y_{n-1}/I_{n-1})ds_n$	

The x-deflection due to the axial redundant force p_0 was

$$\int_0^0 \frac{p_0 y^2}{I}\,ds = 2p_0\int_0^A \frac{y^2}{I}\,ds = 2p_0\sum_1^{n-1}\left[\frac{y_n^2}{I_n} + \frac{(y_{n-1})^2}{I_{n-1}}\right]\frac{ds_n}{2}.$$

The instructions given in gl5, performs the p_0 moment x-deflection. Note that the values of y_{n-1}/I_{n-1} and y_n/I_n formed in gl4, and stored in temporary registers is used in gl5, thus saving operations.

Instruction	Input to MRA	In MRA	Transfer from MRA
gl5, ica tl	$+y_{n-1}/I_{n-1}$	$+y_{n-1}/I_{n-1}$	
imr yl+c	$\times\, y_{n-1}$	$(y_{n-1})^2/I_{n-1}$	
its tl			$(y_{n-1})^2/I_{n-1}$
ica t2	$+y_n/I_n$	$+y_n/I_n$	
imr yl+2+c	$\times\, y_n$	y_n^2/I_n	
ica tl	$+y_{n-1}^2/I_{n-1}$	$y_n^2/I_n+y_{n-1}^2/I_{n-1}$	
imr a5+c	$\times\, ds_n$	$(y_n^2/I_n+y_{n-1}^2/I_{n-1})ds_n$	
iad dl+12	$+\sum_1^{n-1}(y_n^2/I_n+y_{n-1}^2/I_{n-1})ds_n$	$\sum_1^{n}(y_n^2/I_n+y_{n-1}^2/I_{n-1})ds_n$	
its dl+12		$\sum_1^{n}(y_n^2/I_n+y_{n-1}^2/I_{n-1})ds_n$	
ict gll+2	(Cycles back to gll+2).		
isp	(Address set by ita instruction at gll).		

Due to symmetry of the web frame structure, the following redundant integrals are zero. Changes in slope due to q_0.

$$\Delta\theta = \int_0^{0'} \frac{q_0}{I}ds = \int_0^{A} (+x)\frac{q_0}{I}ds + \int_A^{0'} (+x)\frac{q_0}{I}ds = q_0 \int_0^{A}\frac{x}{I}ds + \int_A^{0'}\frac{(-x)}{I}ds = 0$$

Vertical deflection due to m_0 and p_0.

$$\Delta y = \int_0^{O'} \frac{m_0}{I} ds = m_0 \int_0^{A} \frac{x}{I} ds + \int_A^{O'} \frac{(-x)}{I} ds = m_0 \int_0^{A} \frac{x}{I} ds + \int_A^{O'} \frac{(-x)}{I} ds = 0$$

$$\Delta y = \int_0^{O'} \frac{(p_0 y)}{I} ds = p_0 \int_0^{A} \frac{xy}{I} ds + \int_A^{O'} (-x)\frac{y}{I} ds = p_0\ 0 .$$

Horizontal deflection due to q_0.

$$\Delta x = \int_0^{O'} \frac{y(q_0 x)}{I} ds = q_0 \int_0^{A} \frac{xy}{I} ds + \int_A^{O'} (-x)\frac{y}{I} ds = q_0\ 0 .$$

The sub-routines below perform the integration of moments caused by water pressure and weight loads. Note that two programs are necessary since 49 stations are used in the integration but only 25 x and y coordinates had been stored. The following program performs the integration of the moments along the starboard side to find the change in slope for one-half the web.

$$\Delta\theta = \int_0^{A} \frac{m_n}{I} ds = \sum_1^{24} \left(\frac{m_n}{I_n} + \frac{m_{n-1}}{I_{n-1}}\right)\frac{ds}{2}$$

Instruction	Input to MRA	In MRA	Transfer from MRA
gl6, ica b3+c	$+m_{n-1}/I_{n-1}$	$+m_{n-1}/I_{n-1}$	
iad b3+2+c	$+m_n/I_n$	$(m_n/I_n+m_{n-1}/I_{n-1})$	
imr a5+c	$\times\ ds_n$	$(m_n/I_n+m_{n-1}/I_{n-1})ds_n$	
imr cl	$\times\ 1/2$	$(m_n/I_n+m_{n-1}/I_{n-1})ds_n/2$	
iad dl+50	$+\sum_1^{n-1}(m_n/I_n+m_{n-1}/I_{n-1})ds_n/2$	$\sum_1^{n}(m_n/I_n+m_{n-1}/I_{n-1})ds_n/2$	
its dl+50		$\sum_1^{n}(m_n/I_n+m_{n-1}/I_{n-1})ds_n/2$	

The segment of the sub-routine that follows forms the integration of y m_n/I to give the deflections in the x-direction around the starboard half of the web.

Instruction	Input to MRA	In MRA	Transfer from MRA
gl7, ica yl+c	$+y_{n-1}$	$+y_{n-1}$	
imr b3+c	$\times\ m_{n-1}/I_{n-1}$	$y_{n-1}\ m_{n-1}/I_{n-1}$	
its t3			$y_{n-1}\ m_{n-1}/I_{n-1}$
ica yl+2+c	$+y_n$	$+y_n$	
imr b3+2+c	$\times\ m_n/I_n$	$y_n\ m_n/I_n$	
iad t3	$+y_{n-1}\ m_{n-1}/I_{n-1}$	$y_n\ m_n/I_n+y_{n-1}\ m_{n-1}/I_{n-1}$	
imr a5+c	$\times\ ds_n$	$(y_n\ m_n/I_n+y_{n-1}\ m_{n-1}/I_{n-1})ds_n$	

Instruction	Input to MRA	In MRA	Transfer from MRA
(continued)			
imr cl	$\times 1/2$	$(y_n\ m_n/I_n + y_{n-1}\ m_{n-1}/I_{n-1})ds_n/2$	
iad dl+52	$+\sum_{1}^{n-1}(y_n m_n/I_n + y_{n-1}m_{n-1}/I_{n-1})ds_n/2$		
		$\sum_{1}^{n}(y_n m_n/I_n + y_{n-1}m_{n-1}/I_{n-1})ds_n/2$	
its dl+52			$\sum_{1}^{n}(y_n m_n/I_n + y_{n-1}m_{n-1}/I_{n-1})ds_n$

To obtain the deflections in the y-direction on the starboard side due to applied loads, the integral of $x\ m_n/I$ was formed.

$$\Delta y = \int_0^A \frac{xm_n}{I}ds = \sum_1^n \left(\frac{m_{n-1}x_{n-1}}{I_{n-1}} + \frac{m_n x_n}{I_n}\right)\frac{ds_n}{2}$$

Instruction	Input to MRA	In MRA	Transfer from MRA
g18, ica xl+c	$+x_{n-1}$	$+x_{n-1}$	
imr b3+c	$\times m_{n-1}/I_{n-1}$	$x_{n-1}m_{n-1}/I_{n-1}$	
its t3			$x_{n-1}m_{n-1}/I_{n-1}$
ica xl+2+c	$+x_n$	$+x_n$	
imr b3+2+c	$\times m_n/I_m$	$x_n m_n/I_n$	
iad t3	$+x_{n-1}m_{n-1}/I_{n-1}$	$(x_{n-1}m_{n-1}/I_{n-1} + x_n m_n/I_n)$	

Instruction	Input to MRA	In MRA	Transfer from MRA
	(continued)		
imr a5+c	$\times\ ds_n$	$(x_{n-1}m_{n-1}/I_{n-1}+x_n m_n/I_n)ds_n$	
imr c1	$\times\ 1/2$	$(x_{n-1}m_{n-1}/I_{n-1}+x_n m_n/I_n)ds_n/2$	
iad d1+54	$+\sum_{1}^{n-1}(x_{n-1}m_{n-1}/I_{n-1}+x_n m_n/I_n)ds_n/2$		
		$\sum_{1}^{n}(x_{n-1}m_{n-1}/I_{n-1}+x_n m_n/I_n)ds_n/2$	
its d1+54		$\sum_{1}^{n}(x_{n-1}m_{n-1}/I_{n-1}+x_n m_n/I_n)ds_n/2$	
ict g16+2	(Cycles back to g16+2).		

To perform the integrations on the port side, the address changes if the x coordinates, y coordinates and girth segments ds must move up a column of registers. This is accomplished by subtracting 2 from the address for each cycle performed.

Formation of the change in slope due to applied loads (port side)

$$\Delta\theta = \int_{A}^{0'} \frac{m}{I}ds = \sum_{25}^{n}\left(\frac{m_n}{I_n}+\frac{m_{n-1}}{I_{n-1}}\right)\frac{ds_n}{2}$$

Instruction	Input to MRA	In MRA	Transfer from MRA
icr pbl	(Sets cycle counter to number of points in a side)		
g19, ica b3+pal+pal+c	$+m_{n-1}/I_{n-1}$	m_{n-1}/I_{n-1}	
iad b3+2+pal+pal+c	$+m_n/I_n$	$(m_n/I_n+m_{n-1}/I_{n-1})$	
imr a5+pbl+pbl	$\times ds_n$	$(m_n/I_n+m_{n-1}/I_{n-1})ds_n$	
imr cl	$\times 1/2$	$(m_n/I_n+m_{n-1}/I_{n-1})ds_n/2$	
iad d3+50	$+\sum_{1}^{25+n-1}(m_n/I_n+m_{n-1}/I_{n-1})ds_n/2$	$\sum_{1}^{25+n}(m_n/I_n+m_{n-1}/I_{n-1})ds_n/2$	
its d3+50		$\sum_{1}^{25+n}(m_n/I_n+m_{n-1}/I_{n-1})ds_n/2$	

Formation of horizontal deflection port side

$$\Delta x = \int_{A}^{0} \frac{m_n y}{I}\, ds = \sum_{25}^{25+n} \left(\frac{m_{n-1}y_{n-1}}{I_{n-1}} + \frac{m_n y_n}{I_n}\right)\frac{ds_n}{2}$$

Instruction	Input to MRA	In MRA	Transfer from MRA
g20, ica yl+pbl+pbl	y_{n-1}	y_{n-1}	
imr b3+pal+pal+c	$\times m_{n-1}/I_{n-1}$	$y_{n-1}m_{n-1}/I_{n-1}$	
its tl			$y_{n-1}m_{n-1}/I_{n-1}$
ica yl+pbl+pbl-2	$+y_n$	$+y_n$	

Instruction	Input to MRA	In MRA	Transfer from MRA
	(continued)		
imr b3+pal+pal+2+c	$\times m_n/I_n$	$y_n m_n/I_n$	
iad tl	$+m_{n-1}y_{n-1}/I_{n-1}$	$y_n m_n/I_n + y_{n-1}m_{n-1}/I_{n-1}$	
imr a5+pbl+pbl	$\times ds_n$	$(y_n m_n/I_n + y_{n-1}m_{n-1}/I_{n-1})ds_n$	
imr cl	$\times 1/2$	$(y_n m_n/I_n + y_{n-1}m_{n-1}/I_{n-1})ds_n/2$	
iad dl+52	$\sum_{1}^{25+n-1}(y_n m_n/I_n + y_{n-1}m_{n-1}/I_{n-1})ds_n/2$	$\sum_{1}^{25+n}(y_n m_n/I_n + y_{n-1}m_{n-1}/I_{n-1})ds_n/2$	
its dl+52			

Formation of vertical deflection port side due to applied loads.

$$\Delta y = \int_{A}^{0'} \frac{xm_n}{I} ds = \sum_{1}^{25+n} \left(\frac{m_{n-1}x_{n-1}}{I_{n-1}} + \frac{m_n y_n}{I_n}\right)\frac{ds_n}{2}$$

Instruction	Input to MRA	In MRA	Transfer from MRA
ica xl+pbl+pbl	$+x_{n-1}$	$+x_{n-1}$	
imr b3+pbl+pbl+c	$+m_{n-1}/I_{n-1}$	$x_{n-1}m_{n-1}/I_{n-1}$	
its tl			$x_{n-1}m_{n-1}/I_{n-1}$

Instruction	Input to MRA	In MRA	Transfer from MRA
(continued)			
ica x1+pb1+pb1-2	$+x_n$	$+x_n$	
imr b3+pa1+pa1+2+c	$\times m_n/I_n$	$x_n m_n/I_n$	
iad t1	$+x_{n-1}m_{n-1}/I_{n-1}$	$(y_n m_n/I_n + y_{n-1}m_{n-1}/I_{n-1})$	
imr a5+pb1+pb1+c	$\times ds_n$	$(y_n m_n/I_n + y_{n-1}m_{n-1}/I_{n-1})ds_n$	
imr c1	$\times 1/2$	$(y_n m_n/I_n + y_{n-1}m_{n-1}/I_{n-1})ds_n/2$	
iad d1+54	$\sum_{1}^{25+n-1}(x_n m_n/I_n + x_{n-1}m_{n-1}/I_{n-1})ds_n/2$	$\sum_{1}^{25+n}(x_n m_n/I_n + x_{n-1}m_{n-1}/I_{n-1})ds_n/2$	
its d1+54			$\sum_{n}^{25+n}(x_n m_n/I_n + x_{n-1}m_{n-1}/I_{n-1})ds_n/$

The following program changes the addresses of the instructions in g19 and g20 that utilize x, y and ds. The new addresses must move up a column of registers.

OUT (Program goes into Whirlwind mode to change addresses).

Instruction	Input to MRA	In MRA	Transfer from MRA
ca g19+2	imr a5+pbl+pbl	imr a5+pbl+pbl	
su c7	-2 W.W.	imr a5+pbl+pbl-2	
ts g19+2			imr a5+pbl+pbl-2
ts g20+6			imr a5+pbl+pbl-2
ts g20+17			imr a5+pbl+pbl-2
ca g20+3	ica yl+pbl+pbl-2	ica yl+pbl+pbl-2	
ts g20			ica yl+pbl+pbl-2
su c7	-2 W.W.	ica yl+pbl+pbl-4	
ts g20+3			ica yl+pbl+pbl-4
ca g20+14	ica xl+pbl+pbl-2	ica xl+pbl+pbl-2	
ts g20+11			ica xl+pbl+pbl-2
su c7	-2 W.W.	ica xl+pbl+pbl-4	
ts g20+14			ica xl+pbl+pbl-4

IN (Puts computer back in interpreted mode).

ict g19

isp

The above integrations provide the three equations for solving an unsupported ring frame of three degrees of indeterminancy. To solve the subject problem, the equations

$$\int_{B_1}^{B_2} \frac{m(x-x_a)ds}{I} \quad \text{and} \quad \int_{B_3}^{B_4} \frac{m(x-x_b)ds}{I}$$

must be formed and solved simultaneously with the three previously formed. The designations B_1, B_2, B_3 and B_4 are the end points of the two stanchions.

The sub-routine that follows determines the vertical deflection between B_1 and B_2 of the starboard

$$\Delta y = \int_{B_1}^{B_2} \frac{m_n(x-x_a)}{I} ds = \sum_{B_1}^{B_2} \left(\frac{m_n(x_n-x_a)}{I} + \frac{m_{n-1}(x_{n-1}-x_a)}{I_{n-1}} \right) \frac{ds}{2}$$

$$= \sum_{B_1}^{B_2} \left[\frac{m_n(x_n-x_a)}{I_n} \frac{ds}{2} + \frac{m_{n-1}(x_{n-1}-x_a)ds_n}{I_{n-1}\,2} \right]$$

Instruction	Input to MRA	In MRA	Transfer from MRA
ita g21+41			
g21, icr pa5			
ica x1+pb1+c	x_{n-1}	x_{n-1}	
isu x1+pb4	$-x_a$	$(x_{n-1}-x_a)$	
its t3			$(x_{n-1}-x_a)$
imr a5+pn4+c	$\times$ ds	$(x_{n-1}-x_a)ds$	
imr c1	$\times 1/2$	$(x_{n-1}-x_a)ds/2$	
its' t1			$(x_{n-1}-x_a)ds/2$
imr b3+pb4+c	$\times (m/I)_{n-1}$	$(x_{n-1}-x_a)(m/I)_{n-1}ds_n/2 \quad n-1$	
iad d1+56	$+\sum_{B_1}^{n-2}$	$\sum_{B_1}^{n-1}(x_{n-1}-x_a)(m/I)_{n-1}ds_n/2$	

Instruction	Input to MRA	In MRA	Transfer from MRA
	(continued)		
its d1+56		$\sum_{B_1}^{n-1}(x_{n-1}-x_a)(m/I)_{n-1}ds_n/2$	
ica x1+pb4+2	$+x_n$	$+x_n$	
isu x1+pb4	$-x_a$	(x_n-x_a)	
its t4			(x_n-x_a)
imr a5+pb4+c	$\times$ ds	$(x_n-x_a)ds_n$	
imr c1	$\times 1/2$	$(x_n-x_a)ds/2$	
its t2			$ds/2(x_n-x_a)$
imr b3+pb1+pb1+2+c	$x(m/I)_n$	$(m/I)_n(x_n-x_a)ds/2$	
iad d1+56	$+\sum_{B_1}^{B_1+n-1}(m/I)_n(x_n-x_a)ds/2$	$\sum_{B_1}^{B_1+n}(m/I)_n(x_n-x_a)ds/2$	
its d1+56			$\sum_{B_1}^{B_1+n}(m/I)_n(x_n-x_a)ds/2$

The following instructions perform the integration

$$p_0\int_{B_1}^{B_2}\frac{y(x-x_a)}{I}\,ds = p_0\sum\left[\frac{y_n(x_n-x_a)}{I_n}\frac{ds_n}{2}+\frac{y_{n-1}(x_{n-1}-x_a)}{I_{n-1}}\frac{ds_n}{2}\right]$$

Instruction	Input to MRA	In MRA	Transfer from MRA
ica t1	$(x_{n-1}-x_a)ds/2$	$(x_{n-1}-x_a)ds_n/2$	
imr d3+pb4+c	$\times 1/I_{n-1}$	$(x_{n-1}-x_a/I_{n-1})ds_n/2$	
its t1			$(x_{n-1}-x_a/I_{n-1})ds_n/2$
imr y1+pb4+c	$\times y_{n-1}$	$y_{n-1}(x_{n-1}-x_a)/I_{n-1}ds_n/2$	
iad d1+16	$+\sum_{B_1}^{B_1+n-2} y_{n-1}(x_{n-1}-x_a)/I_{n-1}ds_n/2$	$\sum_{B_1}^{B_1+n-1} y_{n-1}(x_{n-1}-x_a)/I_{n-1}ds_n/2$	
its d1+16			$\sum_{B_1}^{B_1+n-1} y_{n-1}(x_{n-1}-x_a)/I_{n-1}ds_n/2$
ica t2	$(x_n-x_a)ds_n/2$	$(x_n-x_a)ds_n/2$	
imr d3+pb4+2+c	$\times (1/I)_n$	$(x_n-x_a)/I_n ds_n/2$	
its t2			$(x_n-x_a)/I_n ds_n/2$
imr y1+pb4+2+c	$\times y_n$	$(x_n-x_a)y_n/I_n ds_n/2$	
iad d1+16	$+\sum_{B_1}^{B_1+n-1} y_{n-1}(x_n-x_a)/I_{n-1}ds_n/2$	$\sum_{B_1}^{B_1+n} y_n(x_n-x_a)/I_n ds_n/2$	
its d1+16			$\sum_{B_1}^{B_1+n} y_n(x_n-x_a)/I_n ds_n/2$

The vertical deflection between the ends of the starboard stanchion due to the redundant q_0 force was found by

$$q_0\int_{B_1}^{B_2} \frac{x(x-x_a)}{I}ds = q_0\sum\left[\frac{x_{n-1}(x_{n-1}-x_a)}{I_{n-1}}\frac{ds_n}{2} + \frac{y_n(x_n-x_a)}{I_n}\frac{ds_n}{2}\right].$$

Instruction	Input to MRA	In MRA	Transfer from MRA
ica t1	$(x_{n-1}-x_a/I_{n-1})ds_n/2$	$(x_{n-1}-x_a)/I_{n-1}ds_n/2$	
imr xl+pb4+c	$\times\ x_{n-1}$	$x_{n-1}(x_{n-1}-x_a)/I_{n-1}ds_n/2$	
iad dl+26	$+\sum_{B_1}^{B_1+n-2} x_{n-1}(x_{n-1}-x_a)/I_{n-1}ds_n/2$	$\sum_{B_1}^{B_1+n-1} x_{n-1}(x_{n-1}-x_a)/I_{n-1}ds_n/2$	
its dl+26			$\sum_{B_1}^{B_1+n-1} x_{n-1}(x_{n-1}-x_a)/I_{n-1}ds_n/2$
ica t2	$(x_n-x_a)/I_n ds_n/2$	$(x_n-x_a)/I_n ds_n/2$	
imr xl+pb4+2+c	$\times\ x_n$	$x_n(x_n-x_a)/I_n ds_n/2$	
iad dl+26	$\sum_{B_1}^{B_1+n-1} x_{n-1}(x_{n-1}-x_a)/I_{n-1}ds_n/2$	$\sum_{B_1}^{B_1+n} x_n(x_n-x_a)/I_n ds_n/2$	
its dl+26			$\sum_{B_1}^{B_1+n} x_n(x_n-x_a)/I_n ds_n/2$

The vertical deflection between the ends of the starboard stanchion due to the redundant column axial force R was found by

$$R\int_{B_1}^{B_2}(x-x_a)\left(\frac{x-x_a}{I}\right)ds = R\sum\left[\frac{(x_n-x_a)^2}{I_n}\frac{ds_n}{2}+\frac{(x_{n-1}-x_a)^2}{I_{n-1}}\frac{ds_n}{2}\right].$$

Instruction	Input to MRA	In MRA	Transfer from MRA
ica t3	$(x_{n-1}-x_a)$	$(x_{n-1}-x_a)$	
imr t1	$\times\ (x_{n-1}-x_a)/I_{n-1}ds_n/2$	$(x_{n-1}-x_a)^2/I_{n-1}ds/2$	
iad d1+36	$+\sum_{B_1}^{B_1+n-2}(x_{n-1}-x_a)^2/I_{n-1}ds_n/2$	$\sum_{B_1}^{B_1+n-1}(x_{n-1}-x_a)^2/I_{n-1}ds_n/2$	
its d1+36			$\sum_{B_1}^{B_1+n}(x_{n-1}-x_a)^2/I_{n-1}ds_n/2$
ica t4	(x_n-x_a)	(x_n-x_a)	
imr t2	$\times\ (x_n-x_a)/I_nds_n/2$	$(x_n-x_a)^2/I_nds_n/2$	
iad d1+36	$+\sum_{B_1}^{B_1+n-1}(x_{n-1}-x_a)^2/I_{n-1}ds/2$	$\sum_{B_1}^{B_1+n-1}(x_n-x_a)^2/I_nds_n/2$	
its d1+36			$\sum_{B_1}^{B_1+n}(x_n-x_a)^2/I_nds_n/2$

The vertical deflection between the two stanchion ends starboard side due to m_0 was performed below.

$$m_0 \int_{B_1}^{B_2} \frac{(x-x_a)}{I}\, ds = m_0 \sum \left[\frac{(x_n-x_a)}{I_n} \frac{ds_n}{2} + \frac{(x_{n-1}-x_a)}{I_{n-1}} \frac{ds_n}{2} \right]$$

Instruction	Input to MRA	In MRA	Transfer from MRA
ica t1	$(x_{n-1}-x_a)/I_{n-1}ds_n/2$	$(x_{n-1}-x_a)/I_{n-1}ds_n/2$	
iad t2	$+ (x_n-x_a)/I_n ds_n/2$	$(x_{n-1}-x_a)/I_{n-1}ds_n/2$ $+(x_n-x_a)/I_n ds_n/2$	
iad d1+6	$+ \sum_{B_1}^{B_1+n-1} (x_{n-1}-x_a)/I_{n-1}$ $+(x_n-x_a)/I_n\ ds_n/2$	$\sum_{B_1}^{B_1+n} (x_{n-1}-x_a)/I_{n-1}ds_{n/2}$ $+(x_n-x_a)/I_n ds_n/2$	
its d1+6			$\sum_{B_1}^{B_1+n} \left[(x_{n-1}-x_a)/I_{n-1} + (x_n-x_a)/I_n\right] ds_n/2$
ict g21+1	(Cycles back through the stanchion integration program).		
isp			

The following sub-routine performs the integrations around the port side which will give the total vertical deflection between the ends of the port stanchion. The entire sum should equal zero, since the stanchion is assumed incompressible.

The instructions that follow perform the integration

$$\Delta y = \int_{B_3}^{B_4} \frac{m_n(x-x_b)}{I}\, ds = \sum_{B_3}^{B_4} \left[\frac{m_n}{I_n}(x_n - x_b) + \frac{m_{n-1}}{I_{n-1}}(x_{n-1} - x_b) \right] \frac{ds_n}{2}$$

Instruction	Input to MRA	In MRA	Transfer from MRA
ita g22+18			
g22, icr pa6			
ica x1+pb5+c	x_{n-1}	x_{n-1}	
isu x1+pb5	$-x_b$	$x_{n-1}-x_b$	
its t3			$(x_{n-1}-x_b)$
imr a5+pb5+c	$\times\ ds_n$	$(x_{n-1}-x_b)ds_n$	
imr c1	$\times\ 1/2$	$(x_{n-1}-x_b)ds_n/2$	
its t1			$(x_{n-1}-x_b)ds_n/2$
imr b3+pb6+pb6	$\times\ (m/I)_{n-1}$	$(m/I)_{n-1}(x_{n-1}-x_b)ds_n/2$	
iad d1+58	$+\sum_{B_3}^{B_3+n-2} (m/I)_{n-1}(x_{n-1}-x_b)ds_n/2$	$\sum_{B_3}^{B_3+n-1} m_n(x_{n-1}-x_b)/I_{n-1}ds_n/2$	
its d1+58			$\sum_{B_3}^{B_3+n-1} m_{n-n}(x_{n-1}-x_b)/I_{n-1}ds_n/2$
ica x1+pb5+2+c	$+x_n$	$+x_n$	
isu x1+pb5	$-x_b$	x_n-x_b	

Instruction	Input to MRA	In MRA	Transfer from MRA
	(continued)		
its t4			x_n-x_b
imr a5+pb5+c	$\times\ ds_n$	$(x_n-x_b)ds_n$	
imr c1	$\times\ 1/2$	$(x_n-x_b)ds_n/2$	
its t2			$(x_n-x_b)ds_n/2$
imr b3+pb6+pb6-2	$\times\ (m/I)_n$	$(m/I)_n(x_n-x_b)ds_n/2$	
iad d1+58	$\sum_{B_3}^{B_3+n-2}(m/I)_{n-1}(x_n-x_b)ds/2$	$\sum_{B_3}^{B_3+n}(m/I)_n(x_n-x_b)ds_n/2$	
its d1+58			$\sum_{B_3}^{B_3+n}(m/I)_n(x_n-x_b)ds_n/2$
OUT			
ca g22+16	imr b3+pb6+pb6-2	imr b3+pb6+pb6-2	
ts g22+7			imr b3+pb6+pb6-2
su c7		imr b3+pb6+pb6-4	
ts g22+16			imr b3+pb6+pb6-4
IN			

The following section of the sub-routine performs the integral

$$p_0\int_{B_3}^{B_4}\frac{y(x-x_b)}{I}ds = p_0\sum\left[\frac{y_{n-1}(x_{n-1}-x_b)}{I_{n-1}}+\frac{y_n(x_n-x_b)}{I_n}\right]\frac{ds_n}{2}$$

Instruction	Input to MRA	In MRA	Transfer from MRA
ica t1	$(x_{n-1}-x_b)ds_n/2$	$(x_{n-1}-x_b)ds_n/2$	
imr d3+pb5+c	$x(1/I)_{n-1}$	$(x_{n-1}-x_b)/I_{n-1}ds_n/2$	
its t1			$(x_{n-1}-x_b)/I_{n-1}ds_n/2$
imr y1+pb5+c	$\times y_{n-1}$	$y_{n-1}(x_{n-1}-x_b)/I_{n-1}ds_n/2$	
iad d1+18	$\sum_{B_3}^{B_3+n-2} y_n(x_n-x_b)/I_n ds_n/2$	$\sum_{B_3}^{B_3+n-1} y_{n-1}(x_{n-1}-x_b)/I_{n-1}ds_n/2$	
its d1+18			$\sum_{B_3}^{B_3+n-1} y_{n-1}(x_{n-1}-x_b)/I_{n-1}ds_n/2$
ica t2	$(x_n-x_b)ds_n/2$	$(x_n-x_b)ds_n/2$	
imr d3+pb5+2+c	$\times 1/I_n$	$(x_n-x_b)/I_n ds_n/2$	
its t2			$(x_n-x_b)/I_n ds_n/2$
imr y1+pb5+2+c	xy_n	$y_n(x_n-x_b)/I_n ds_n/2$	
iad d1+18	$\sum_{B_3}^{B_3+n-1} y_{n-1}(x_{n-1}-x_b)/I_{n-1}ds_n/2$	$\sum_{B_3}^{B_3+n} y_n(x_n-x_b)/I_n ds_n/2$	
its d1+18			$\sum_{B_3}^{B_3+n} y_n(x_n-x_b)/I_n ds_n/2$

The following section of the sub-routine performs the integration

$$q_0 \int_{B_3}^{B_4} \frac{x(x-x_b)}{I}\,ds = q_0 \sum_{B_3}^{B_4} \left[\frac{x_n(x_n-x_b)}{I_n}\frac{ds}{2} + \frac{x_{n-1}(x_{n-1}-x_b)}{I_{n-1}} \right] \frac{ds}{2}$$

Instruction	Input to MRA	In MRA	Transfer from MRA
ica t1	$(x_{n-1}-x_b)/I_{n-1}ds_n/2$	$(x_{n-1}-x_b)/I_{n-1}ds_n/2$	
imr x1+pb5+c	$\times\ x_{n-1}$	$x_{n-1}(x_{n-1}-x_b)/I_{n-1}ds_n/2$	
iad d1+28	$\sum_{B_3}^{B_3+n-2} x_n(x_n-x_b)/I_n ds/2$	$\sum_{B_3}^{B_3+n-1} x_{n-1}(x_{n-1}-x_b)/I_{n-1}ds_n/2$	
its d1+28			$\sum_{B_3}^{B_3+n-1} x_{n-1}(x_{n-1}-x_b)/I_{n-1}ds_n/2$
ica t2	$(x_n-x_b)/I_n ds_n/2$	$(x_n-x_b)/I_n ds_n/2$	
imr x1+pb5+2+c	$\times\ x_n$	$x_n(x_n-x_b)/I_n ds_n/2$	
iad d1+28	$\sum_{B_3}^{B_3+n-1} x_{n-1}(x_n-x_b)/I_{n-1}ds_n/2$	$\sum_{B_3}^{B_3+n-1} x_{n-1}(x_n-x_b)/I_n ds_n/2$	
its d1+28			$\sum_{B_3}^{B_3+n} x_n(x_n-x_b)/I_n ds_n/2$

The following section of the sub-routine forms the vertical deflection caused by the axial stanchion force redundant S.

$$\Delta y = S\int_{B_3}^{B_4} \frac{(x-x_b)(x-x_b)}{1I}\,ds = S\sum_{B_3}^{B_4}\left[\frac{(x_n-x_b)^2}{I_n}\,\frac{ds_n}{2} + \frac{(x_{n-1}-x_b)^2}{I_{n-1}}\right]\frac{ds_n}{2} .$$

Instruction	Input to MRA	In MRA	Transfer from MRA
ica t3	$x_{n-1}-x_b$	$(x_{n-1}-x_b)$	
imr t1	$\times\,(x_{n-1}-x_b)/I_{n-1}ds_n/2$	$(x_{n-1}-x_b)^2/I_{n-1}ds_n/2$	
iad d1+48	$\sum_{B_3}^{B_3+n-2}(x_{n-2}-x_b)^2/I_{n-2}ds_n/2$	$\sum_{B_3}^{B_3+n-1}(x_{n-1}-x_b)^2/I_{n-1}ds_n/2$	
its d1+48			$\sum_{B_3}^{B_3+n-1}(x_{n-1}-x_b)^2/I_{n-1}ds_n/2$
ica t4	(x_n-x_b)	(x_n-x_b)	
imr t2	$\times\,(x_n-x_b)/I_nds_n/2$	$(x_n-x_b)^2/I_nds_n/2$	
iad d1+48	$\sum_{B_3}^{B_3+n-1}(x_{n-1}-x_b)^2/I_{n-1}ds_n/2$	$\sum_{B_3}^{B_3+n}(x_{n-1}-x_b)^2/I_nds_n/2$	
its d1+48			$\sum_{B_3}^{B_3+n}(x_n-x_b)^2/I_nds_n/2$

The following section of the sub-routine finds the vertical deflection caused by the redundant moment m_0.

$$\Delta y = m_0 \int_{B_3}^{B_4} \frac{(x-x_b)}{I}\, ds = m_0 \sum_{B_3}^{B_4} \left[\frac{(x_n - x_b)}{I_n} \frac{ds_n}{2} + \frac{(x_{n-1} - x_b)}{I_{n-1}} \right] \frac{ds_n}{2}$$

Instruction	Input to MRA	In MRA	Transfer from MRA
ica t1	$(x_{n-1}-x_b)/I_{n-1} ds_n/2$	$(x_{n-1}-x_b)/I_{n-1} ds_n/2$	
iad t2	$(x_n-x_b)/I_n ds_n/2$	$(x_{n-1}-x_b)/I_{n-1} ds_n/2 + (x_n-x_b)/I_n ds_n/2$	
iad d1+8	$\sum_{B_3}^{B_3+n-1} \left[(x_{n-1}-x_b)/I_{n-1} + (x_n-x_b)/I_n \right] ds_n/2$	$\sum_{B_3}^{B_3+n} \left[(x_{n-1}-x_b)/I_{n-1} ds_n/2 + (x_n-x_b)/I_n ds_n/2 \right]$	
its d1+8			$\sum_{B_3}^{B_3+n} \left[(x_{n-1}-x_b)/I_{n-1} + x_n-x_b/I_n \right] ds_n/2$
ict g22+1	(Cycles back to g22+1).		

The redundant stanchion forces affect the deflections for the web as a whole in much the same manner as the three basic redundant forces affect the deflection around the two stanchion sections. An analysis of Figure VI shows that the integrals of p_0, q_0, and m_0 for the traverse around the stanchion loop is the same as the integrals of R and S about

the entire web girth. Therefore, the coefficients of the redundants which are the integrals may be used in several places. As an examle the coefficient of the deflection magnitude due to m_0 between B_1 and B_2 is the same as the coefficient of the angular rotation magnitude due to the redundant R about the entire girth. Moment due to R is $R(x-x_a)$ and the rotation due to the moment is

$$R\int_0^{0'} \frac{(x-x_a)}{I}\,ds = R\int_0^{B_1} \frac{(x-x_a)}{I}\,ds + \int_{B_1}^{B_2} \frac{(x-x_a)}{I}\,ds + \int_{B_2}^{0'} \frac{(x-x_a)}{I}\,ds.$$

The deflection between B_1 and B_2 due to m_0 is

$$m_0\int \frac{(x-x_a)}{I}\,ds.$$

The following instructions utilize the computed coefficients to fill similar values.

Instruction	Input to MRA	In MRA	Transfer from MRA
ica dl+6	$\int_{B_1}^{B_2}(x-x_a)/I ds$	$+\int_{B_1}^{B_3}(x-x_a)/I ds$	
its dl+30			$\int_{B_1}^{B_3}(x-x_a)/I ds$
ica dl+16	$\int_{B_1}^{B_2}y(x-x_a)/I ds$	$+\int_{B_1}^{B_2}y(x-x_a)/I ds$	

(continued)

Instruction	Input to MRA	In MRA	Transfer from MRA
its dl+32			$+\int_{B_1}^{B_2} y(x-x_a)/Ids$
ica dl+26	$+\int_{B_1}^{B_2} x(x-x_a)/Ids$		
its dl+34			$\int_{B_1}^{B_2} x(x-x_a)/Ids$
ica dl+8	$\int_{B_3}^{B_4} (x-x_b)/Ids$		
its dl+40			$\int_{B_3}^{B_4} (x-x_b)/Ids$
ica dl+18	$\int_{B_3}^{B_4} y(x-x_b)/Ids$		
its dl+42			$\int_{B_3}^{B_4} y(x-x_b)/Ids$
ica dl+28	$\int_{B_3}^{B_4} x(x-x_a)/Ids$		

Instruction	Input to MRA	In MRA	Transfer from MRA
	(continued)		
its dl+32			$+\int_{B_1}^{B_2} y(x-x_a)/Ids$
ica dl+26	$+\int_{B_1}^{B_2} x(x-x_a)/Ids$		
its dl+34			$\int_{B_1}^{B_2} x(x-x_a)/Ids$
ica dl+8	$\int_{B_3}^{B_4} (x-x_b)/Ids$		
its dl+40			$\int_{B_3}^{B_4} (x-x_b)/Ids$
ica dl+18	$\int_{B_3}^{B_4} y(x-x_b)/Ids$		
its dl+42			$\int_{B_3}^{B_4} y(x-x_b)/Ids$
ica dl+28	$\int_{B_3}^{B_4} x(x-x_a)/Ids$		

Instruction	Input to MRA	In MRA	Transfer from MRA

(continued)

its d1+44			$\int_{B_3}^{B_4} x(x-x_a)/I ds$
isp			

The following sub-routine reduces the matrix of deflection equations by Crout's method and finds values for all redundants. The sub-routine, designated by S2, is a routine contained in the library of the computer laboratory. The library routines have been tested and tried and are known to be correct. For this reason only the method of entering the routine will be given.

Instruction	Input to MRA	In MRA	Transfer from MRA
ita g23+5			
OUT			
g23, SP S2			
d1	Address of first column.		
5	Order of matrix.		
1	Number of columns of constants		
IN			
isp			

The instructions below alter the vertical and horizontal forces to include the redundant forces p_0, q_0, R and S. Note that each redundant is applied as a load at its point of action.

$$H_2 = H_1 - p_0 \qquad V_2 = V_1 - q_0 + R + S.$$

Instruction	Input to MRA	In MRA	Transfer from MRA
ita g24+25			
g24, ica e5	$+V_n$	$+V_n$	
isu d1+54	q_0	V_n-q_0	
its e5			V_n-q_0
	The following instructions form $H-p_0$		
ica e3	$+H_w$	$+H_w$	
isu d1+52	$-p_0$	H_w-p_0	
its e3			H_w-p_0
	The following instructions form V-R		
ica e5+pb4	$+V_n$	$+V_n$	
isu d1+56	$-R$	V_n-R	
its e5+pb4			V_n-R
ica e5+pb5+pa5+pa5	$+V_n$	$+V_n$	
iad d1+56	$+R$	V_n+R	
its e5+pb4+pa5+pa5			V_n+R
ica e5+pb6+pb6	$+V_n$	$+V_n$	
isu d1+58	$+S$	V_n+S	
its e5+pb6+pb6			V_n+S
ica ab6+pb6-pa6-pa6	$+V$	$+V$	
iad d1+58	$+S$	$+V+S$	
its pb6+pb6-pa6-pa6			$V+S$

The Whirlwind instructions that follow change the address of g24+16 and g24+18.

Instruction	Input to MRA	In MRA	Transfer from MRA
OUT			
ca g24+16	ica e5+pb6+pb6-2	ica e5+pb6+pb6-2	
su c7	-2	ica e5+pb6+pb6-4	
ts g24+16			ica e5+pb6+pb6-4
td g24+18			e5+pb6+pb6-4
IN			
ict g24+16			

The following sub-routine finds the stresses at each station due to the axial loads (p), the shear loads (q) and the bending moments (m). After the various stresses have been formed the direct stresses and the maximum compression and tension bending stresses are combined to form the total stresses at the flange and at the shell surface. The relationships listed below are utilized in the sub-program.

$$p = H \cos \phi - V \sin \phi$$

$$q = H \sin \phi - V \cos \phi$$

Direct stress $\sigma_a = p/A$

Shear stress $\sigma_b = q/A$

Bending Stresses $= my/I$

$$\sigma s_m = \text{shell}_m = m/I\ (d_{N.A.} + t_s)$$

$$\sigma f_m = \text{flange}_m = m/I\ (t_f + d_w - d_{N.A.})$$

$$\sigma_s = \sigma_a \pm \sigma s_m$$

$$\sigma_f = \sigma_a \pm \sigma f_m$$

The following instructions use the above relationships for the starboard side of the frame.

Instruction	Input to MRA	In MRA	Transfer from MRA
ita g27			
g25, ica c6	+0.0	+0.0	
its t8			+0.0 in t8
its t7			+0.0
icr pal			
ica t8	$+\sum^{n-1} V$	$+\sum^{n-1} V$	
iad e5+c	+V	$+\sum^{n} V$	
its t8			$\sum^{n} V$
imr a1+c	$\times \sin \phi$	$\sum^{n} V \sin \phi$	
its t1			$\sum^{n} V \sin \phi$
ica t7	$+\sum^{n-1} H$	$+\sum^{n-1} H$	
iad e3+c	+H	$+\sum^{n} H$	
its t7			$\sum^{n} H$
imr a2+c	$\times \cos \phi$	$\sum^{n} H \cos \phi$	
isu t1	$-V \sin \phi$	$\sum H \cos \phi - \sum V \sin \phi = p$	

Instruction	Input to MRA	In MRA	Transfer from MRA
	(continued)		
idv d2+c	$\div$ A	p/A	
imr el	$\times$ 8	8 p/A	
its xl+c			$p/A = \sigma$
ica t8	$+\sum^{n} V$	$+\sum^{n} V$	
imr a2+c	$\times \cos \phi$	$\sum^{n} V \cos \phi$	
its tl			$\sum^{n} V \cos \phi$
ics t7	$+\sum^{n} H$	$+\sum^{n} H$	
imr al	$\times \sin \phi$	$\sum^{n} H \sin \phi$	
isu tl	$-\sum^{n} V \cos \phi$	$\sum^{n} H \sin \phi - \sum^{n} V \cos \phi = q$	
idv d2+c	$\div$ A	q/A	
imr el	$\times$ 8	8 q/A	
its sl+c			$8\ q/A = \sigma_b$

Note that σ_b was formed using the entire area as effective in shears. This is an error which should be corrected since only the area of the web is effective in shear.

Instruction	Input to MRA	In MRA	Transfer from MRA
ics dl+c	$-d_{N.A.}$	$-d_{N.A.}$	

Instruction	Input to MRA	In MRA	Transfer from MRA
	(continued)		
isu b5+c	$-t_s$	$-(d_{N.A.}+t_s)$	
imr c15	$\times$ 12	$-12(d_{N.A.}+t_s)$	
imr b3+c	$\times$ m/I	$-12\ m/I(d_{N.A.}+t_s) = \sigma_{sm}$	
imr e1	$\times$ 8	$-96\ m/I(d_{N.A.}+t_s) = -\sigma_{sm}$	
iad x1+c	$+{}_{a}$	$-(\sigma_{sm}-\sigma_a) = \sigma_s$	
its a5+c			σ_s
ica b1+c	$+d_w$	$+d_w$	
iad b4+c	$+t_f$	d_w+t_f	
isu d1+c	$-d_{N.A.}$	$(d_w+t_f-d_{N.A.})$	
imr c15	$\times$ 12	$12(d_w+t_f-d_{N.A.})$	
imr b3+c	$\times$ m/I	$12\ m/I(d_w+t_f-d_{N.A.})$	
imr e1	$\times$ 8	$96\ m/I(d_w+t_f-d_{N.A.}) = \sigma_{fm}$	
iad x1+c	$+{}_{a}$	$\sigma_{fm}+\sigma_a = \sigma_f$	
its e5+c			σ_f
ict g25+34			

The following instructions calculate the stresses around the port side.

Instruction	Input to MRA	In MRA	Transfer from MRA
icr pb1			
g26, ica t8	$+\sum^{n-1} V$	$+\sum^{n-1} V$	
iad e5+pa1+pa1+c	$+V$	$\sum^{n} V$	
its t8			$\sum^{n} V$
imr a1+pb2+pb2	$\times \sin\phi$	$\sin\phi \sum^{n} V$	
its t1			$+\sin\phi \sum^{n} V$
ica t7	$+\sum^{n-1} H$	$\sum^{n-1} H$	
isu e3+pb2+pb2	$+H$	$\sum^{n} H$	
its t7			$\sum^{n} H$
imr a2+pb2+pb2	$\times \cos\phi$	$\cos\phi \sum^{n} H$	
iad t1	$+\sin\phi \sum^{n} V$	$\cos\phi \sum^{n} H + \sin\phi \sum^{n} V = p$	
idv d2+pb2+pb2	$\div A$	$p/A = \sigma_a$	
its x1+pa1+pa1+c			$p/A = \sigma_a$

(continued)

Instruction	Input to MRA	In MRA	Transfer from MRA
ica t8	$\sum^{n} V$	$\sum^{n} V$	
imr a2+pb2+pb2	$\times \cos \phi$	$\cos \phi \sum^{n} V$	
its t1			$\cos \phi \sum^{n} V$
ica t7	$\sum^{n} H$	$\sum^{n} H$	
imr a1+pb2+pb2	$\times \sin \phi$	$\sin \phi \sum^{n} H$	
isu t1	$-\cos \phi \sum^{n} V$	$+(\sin \phi \sum^{n} H - \cos \phi \sum^{n} V) = q$	
idv d2+pb2+pb2	$\div A$	$q/A = \sigma_b$	
its s1+pa1+pa1+c			σ_b
ics d1+pb2+pb2	$-d_{N.A.}$	$-d_{N.A.}$	
isu b5+pb2+pb2	$-t_s$	$-(d_{N.A.}+t_s)$	
imr b3+pa1+pa1+c	$\times m/I$	$-m/I(d_{N.A.}+t_s) = -\sigma_{sm}$	
isu x1+pa1+pa1+c	$-\sigma_a$	$-({}_a + {}_{sm}) = \sigma_s$	
its a5+pa1+pa1+c			σ_s

Instruction	Input to MRA	In MRA	Transfer from MRA

(continued)

ics d1+pb2+pb2	$-d_{N.A.}$	$-d_{N.A.}$	
iad b4+pb2+pb2	$+t_f$	$-d_{N.A.}+t_f$	
iad b1+pb2+pb2	$+d_W$	$(d_W+t_f-d_{N.A.})$	
imr b3+pa1+pa1+c	$\times$ m/I	$m/I(d_W+t_f-d_{N.A.}) = \sigma_{fm}$	
iad x1+pa1+pa1+c	$-\sigma_a$	$\sigma_{fm}-\sigma_a=\sigma_f$	
its e5+pa1+pa1+c			σ_f

OUT (The following instructions change the addresses of the above program).

ca g26+3	imr a1+pb2+pb2	imr a1+pb2+pb2	
su c7	-2	imr a1+pb2+pb2-2	
ts g26+3			imr a1+pb2+pb2-2
ts g26+17			
ca g26+7	iad e3+pb2+pb2	iad e3+pb2+pb2	
su c7	-2	iad e3+pb2+pb2-2	
ts g26+7			iad e3+pb2+pb2-2
ca g26+9	imr a2+pb2+pb2	imr a2+pb2+pb2	
su c7	-2	imr a2+pb2+pb2-2	
ts g26+9			imr a2+pb2+pb2-2
ts g26+14			imr a2+pb2+pb2-2
ca g26+11	idv d2+pb2+pb2	idv d2 +pb2+pb2	
su c7	-2	idv d2+pb2+pb2-2	
ts g26+11			idv d2+pb2+pb2-2

Instruction	Input to MRA	In MRA	Transfer from MRA
	(continued)		
ts g26+18			idv d2+pb2+pb2-2
ca g26+20	ics dl+pb2+pb2	ics dl+pb2+pb2	
su c7	-2	ics dl+pb2+pb2-2	
ts g26+20			ics dl+pb2+pb2-2
ts g26+25			ics dl+pb2+pb2-2
ca g26+21	isu b5+pb2+pb2	isu b5+pb2+pb2	
su c7	-2	isu b5+pb2+pb2-2	
ts g26+21			isu b5+pb2+pb2-2
ca g26+26	iad b4+pb2+pb2	iad b4+pb2+pb2	
su c7	-2	iad b4+pb2+pb2-2	
ts g26+26			iad b4+pb2+pb2-2
ca g26+27	iad bl+pb2+pb2	iad bl+pb2+pb2	
su c7	-2	iad bl+pb2+pb2-2	
ts g26+27			iad bl+pb2+pb2-2
IN			
ict g26			
g27, isp			

Appendix C

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